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Central Electricity Generating Board

GENERATION AND TRANSMISSION SYSTEMS FOR WAVE POWER

- A FEASIBILITY STUDY -

The first report of Technical Advisory Group 6 (Generation and Transmission) of the Wave Energy Steering Committee

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WAVE ENERGY STEERING COMMITTEE

Generation and Transmission Systems
A Feasibility Study

Report of the First Stage Study
by TAG 6 to WESC

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DEPARTMENT OF ENERGY

WAVE ENERGY STEERING COMMITTEE

GENERATION AND TRANSMISSION SYSTEMS - A FEASIBILITY STUDY

(The Report of the first Stage Study by WESC TAG 6)

EXECUTIVE SUMMARY

During the past 10 months TAG 6 has undertaken a wide ranging study of conceptual generation and transmission systems with the objective of identifying those suitable for detailed examination on an 18 month Stage II study for the remainder of Phase I.

The main report describes the assumptions of WEC size and performance and the basis for interpreting model tests to full scale (Section 4 and Appendix I). TAG 6 has found it convenient to separately define 'ratings' of WECs in terms of (i) Maximum Continuous Rating (MCR) which is the design rms output from the WEC at full load, and a load factor of about 70%. (ii) Peak rating which is the maximum power overload needed to achieve MCR and (iii) an output which is the final continuous rating of the system after accounting for generation and transmission efficiencies.

The major part of the study, summarised in Section 5, has been a technical examination of components which could be employed in the conceptual generation and transmission systems against the assumed specifications. The main conclusions from this technical assessment are set out in Section 7 and represent a very significant narrowing of the field leaving -

(a) Four mechanical power take offs

- (i) geared drive to hydraulic pumps;
- (ii) geared drive to electrical generators;
- (iii) cam driven hydraulic rams;
- (iv) crank driven hydraulic rams.

(b) Two basic designs of electrical generator - both synchronous type alternators

- (i) variable speed - including reversing motion;
- (ii) hydraulically driven at nominally fixed speed.

Alternators for OWCs and HRS rectifiers are in the second category.

(c) Three approaches to electrical transmission dependent on the alternator operation

- (i) for nominally fixed speed alternators, series connected WECs and HVDC transmission to shore;
- (ii) for variable speed alternator, a DC control link and HVAC transmission to shore;
- (iii) for the HRS rectifier only, when sea bed standing close to the mainland, synchronous operation of the alternators connected directly to a grid link.

Excluding alternators, the transmission schemes will cost ∿ £210/kW(i) to £36/kW (ii) referred to the output rating, and on shore transmission to the CEGB adds ∿ £90/kW.

Non electrical transmission routes have been found to be less favourable.

(a) Hydrogen produced on board the WEC has a minimum landed cost of 1.4p/kWh_{th} (41p/therm). This estimate is expected to increase as revised WEC and generator drive costs are included.

(b) Hot Water is a feasible transmission medium but supplies 130C water at $\sim$ 0.9p/kWh_{th} (26p/therm) with no identifiable market.

(c) Hydraulic transmission is about three times the cost of electrical transmission and is less efficient overall.

All generation and transmission systems are expensive, section 9 and Appendix IV. Costs given should be treated as indicative and not definitive because of the major uncertainties in the design of power take off systems, especially for ducks and rafts, which often contain items outside of current manufacturing experience. The inclusion of costs is justified for the purpose of identifying sensitive areas.

Systems for taking power from ducks and rafts can be expected to cost £600 to £3,000/kW_{out} according to the system selected. Gear driven alternators and rotary pumps and ram pump/hydraulic motor drives to alternators are preferred but cannot be separated because of design and manufacturing uncertainties.

Generation and transmission from OWCs and HRS rectifiers is simpler, cheaper and more efficient and the structures and primary drives for these devices could be £200 to £600/kW at MCR more expensive than competitive ducks or rafts. In the range of WEC costs of £200 to £800/kW at MCR, the range of delivered energy costs are 1.5p to 4.5p/kWh_e for duck and raft systems and 1.0p to 2.3p/kWh_e for OWCs and HRS rectifiers, delivered from Scotland to the CEGB in both cases. The readers attention is drawn to the cautionary note in Appendix IV section 5 regarding the interpretation of these figures which are only comparable if WEC costs have been determined on a common basis and that ducks and rafts could still prove to be cheapest overall.

Cost sensitivity considerations point to the need to

(a) Establish the relative costs of WEC structures on a common basis which has to be determined in discussions throughout the WESC organisation

(b) Minimise hydraulic or other storage on the WEC by

(c) achieving maximum smoothing through hydraulic or electrical interconnection of WECs.

(d) Examine gears bearings and seals and cam and crank driven rams in detail for raft and duck systems.

Details of information needed from device teams are set out in section 10 and a full set of areas recommended for further study by TAG 6 are set out in section 11 including those areas where an input from other TAGS will be required.

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1. INTRODUCTION

Following his recommendation to WESC, Dr. J.K. Wright was asked to approach GEC, Joseph Lucas and IRD with a view to seeking their support in assessing the technical feasibility and cost of converting wave energy, available in some mechanical form at the output of a device (WEC), to a more usable form for consumption on the UK mainland. At this time it was anticipated that this usable form would be electricity which would be fed into the CEGB/Scottish Boards grid network but it was also agreed that other energy forms were to be included.

Early agreement by the companies on the desirability of such a study and discussions on how it might proceed led to the proposal 'Getting the Power to Shore' (1). The overall objectives of the study were agreed as

(i) to identify and assess possible energy conversion and transmission system;

(ii) estimate the performance and cost of the more promising systems and make a first order assessment of the impact of the operational and performance characteristics of particular designs on the overall economics of WEC systems;

(iii) provide design information for the device teams developing particular WECs - both through independent studies and by way of consultancies;

(iv) estimate the timescales and the R & D effort required to implement particular designs.

The very large number of possible routes, the unfamiliar characteristics of the energy supply and the 'fluid' state of the thinking of the device teams were all factors which led TAG 6 to propose a preliminary, 9 month, 'broad brush' study as a necessary precursor to a detailed study of preferred systems. It is this preliminary study which is the subject of the present report. The succeeding sections of the report set out the specific objectives of the preliminary survey, set out the system options, discuss the assumptions which have been made in relation to wave and device properties and then discuss specific elements of the possible systems. The final sections relate these generic considerations to specific device designs and describe the preferred systems, ranked in order of technical 'credibility' and cost, which TAG 6 believe should be examined in greater detail during the second stage of its phase I study.

Frequent reference is made to the working papers which have been prepared in the course of this study (a total of more than sixty are listed in Appendix III). It goes without saying that these papers are available for examination by anyone who wishes to obtain background information and supporting technical detail but the reader is asked to note that these are working papers and do not necessarily represent the present views of TAG 6. It would be surprising if detailed studies during stage II, when better information is available from device teams and the other TAGs, do not give rise to further shifts of emphasis.

2. OBJECTIVES OF THE TAG 6 STAGE I STUDY

One of the most valuable achievements of the study, which could have been declared as an objective, has been the education of a diverse group of experts from the power engineering industry to the special requirements of Wave Energy Conversion.

This has been effected through meeting the following specific objectives:

(i) to rank the conceptual systems in terms of cost and technical feasibility and for their compatibility with the device teams' proposals and, where necessary, recommend changes in device design and additional experimental studies;

by (ii) to identify possible, conceptual, generation and transmission systems to convert mechanical energy at the device to a usable form and transmit it to shore;

(iii) to carry out an outline design study of the component parts and their possible combination for each of the device types proposed paying particular attention to the characteristics of the wave energy supply and to the requirement for a 'smooth' delivery to the grid/consumer;

(iv) to obtain a first estimate of required component ratings, physical sizes, performance and overall operational characteristics.

These meet the first and some aspects of the second and third objectives of the overall study.

3. POSSIBLE GENERATION AND TRANSMISSION SYSTEMS

A series of visits to the device teams and discussions by the members of TAG 6 (GEC, LUCAS, IRD and CEGB) resulted in the identification of the main system options given in the advisory groups proposal (1). These are reproduced here in slightly modified form as Figure 1.

The first thing to note is the inclusion of the 'wave' and the 'device' despite the fact that these, together with the first stage of conversion, are primarily the responsibility of TAG 2 and the device teams. From the beginning it has been clear that if the energy input were smooth, and only slowly varying, then, apart from questions of 'marinisation' generation and transmission would present no problems and the study would simply reduce to a cost comparison. The characteristics of the wave energy supply on all timescales and the response characteristics of the device, must therefore be included if the generation and transmission study is to have any value. Neither TAG 2 nor the device teams were in a position to provide all the necessary background information and it has fallen to the CEGB to specify the main input parameters on the basis of their own studies in support of WESC.

It is recognised that much of this input is based on theoretical considerations and will be subject to modification as the total study progresses. It must be emphasised that there has been no desire at any stage to usurp the positions of the device teams.

The primary output of the Salter and Cockerell designs, which are of the same generic type, is derived from the random mechanical motion of one structure (duck or raft) relative to another (spine or second raft). It is characterised by very small relative velocities at very low frequencies ($\sim$ 0.1 Hz) and varies from second to second, hour to hour and sea state to sea state. The OWC has a basically similar output, one of the structures being replaced by the water column, but an air interface and an air turbine are essential features of the design. The output from the OWC is still randomly varying at the wave frequency but velocities at the air turbine output shaft are able to be substantially higher than for the directly coupled devices. Only the H.R.S. Rectifier in its basic form is significantly different since it is presumed to have substantial inbuilt storage so enabling a continuous output to be produced.

The mechanical motions of the Salter/Cockerell systems first have to be transferred to a secondary energy conversion system. Figure 1 indicates a range of possibilities from speed increasing (by lever, gear, etc.) to a (relatively) high speed hydraulic pump or electrical generator, through hydraulic pumps or electrical generators operating directly off the device without speed increase to the simplest secondary converter involving, for example, a water heating brake. None of these primary conversion techniques particularly limit the possibilities in the later stages of conversion and transmission but potentially the hydraulic approach lends itself more easily to the incorporation of storage at the WEC and the interconnection, either hydraulically or electrically, of adjacent systems. The direct generation of electricity involves fewer conversion stages and is potentially more efficient but interconnection is conceptually far more difficult and storage improbable. All of hydraulic, electric and thermal transmission are possible and, as one means of interconnecting adjacent systems, electrolytically produced hydrogen, which could be piped or tankered to shore, is a further transmission and storage option.

The range of possible final products is just as varied. As indicated in the Introduction, first choice is smooth 50 Hz AC electricity delivered to the UK electrical grid system. Alternatives are:

(i) fuel for electricity generation/process industries, i.e. hydrogen or its derivatives;

(ii) fuel for substitution, e.g. hydrogen or its derivatives for automative applications,

(iii) thermal energy for heating or power generation, as hot water, and

(iv) fuel (as uranium) and other heavy metal resources derived from wave powered sea water separation plant.

This last has not been examined by TAG 6 but is the subject of a CEGB assessment and will be reported to WESC in due course. The other options reduce to:

(i) electricity generated at sea and transmitted to shore;

(ii) electricity generated on shore or at some intermediate 'collecting point' from transitted hydrogen, hot water or high pressure fluid, and

(iii) hydrogen, hot water or high pressure fluid transmitted to shore for purposes other than electricity generation.

TAG 6 has quite deliberately not selected particular complete wave-to-shore systems to make a study of each one in its entirety. At the outset there were too many permutations to be certain of choosing the most appropriate schemes for analysis and, more importantly, such studies could not be undertaken in any meaningful sense until the full impact of the unusual power distribution from a WEC on the design and operation of individual components and the problems of device interconnection had been assessed. The group has instead concentrated on the assessment of specific plant items, gears, hydraulic pumps, electric generators, etc., against an input specification derived from wave and device characteristics both in the general sense and, towards the end of the study, for particular device designs.

4. WAVE AND DEVICE PROPERTIES - AN INPUT SPECIFICATION

At the start of the study, the input parameters could only be specified as averages, albeit over a wide range, but it was recognised from the outset that all the mechanical, hydraulic and electrical components which precede either storage equipment or a major interconnection point (to which a sufficient number of separate uncorrelated random inputs are introduced to produce a substantially smooth output) will be subjected to the full randomness of the wave/mechanical input. It follows that peak ratings of torque, power transfer, or even just velocity or displacement are likely to be the limiting parameters on a particular design. TAG 6 has therefore made assumptions of the wave climate and particular device performances to produce estimates of the range of operating conditions and has followed this up with theoretical studies to refine the input specification in readiness for the second stage.

4.1 Wave Climate

It has been assumed that the wave climate at the generating site is the same as that reported for Station India (2) and that devices will therefore be required to operate in calm and near calm conditions, moderate height swells and a range of fully developed seas up to that corresponding to a 50 year wave of 34 m.

To ensure that the TAG 6 assessment took an adequate range of wave conditions into account, a total of nine wave states were specified (3) in terms of H_s and T_z. The first six were selected to cover the full range of developed seas at India and each was assumed to have its energy distributed with frequency according to the Pierson-Moskowitz spectral density function conveniently described as a function of H_s and T_z in (4). In addition, three possible swell seas were included which, although they may turn out not to be realistic, do represent different power extremes which should be considered.

The nine wave states and the incident rms wave powers are set out in Table 1 and are not to be confused with the conventional 'sea state' classification.

Wave state	H_s(m)	T_z(sec)	rms power (kW/M)	
1	8	7	34.7	
2	1	7	3.9	
3	7	9	24.2	
4	3	9	44.6	
5	14	14	1509	
6	4	14	123	
7	1	7	7	swell
8	3	9	81	"
9	4	14	224	"

TABLE 1: STAGE I DATA BASE - WAVE STATES

Wave states 1 to 4 and 7 represent the most significant section of the wave climate and 5 is a typical 'survival' wave state. In general a good performance in the more modest conditions is essential to system economics and a poor response to 5 is required if expensive protection systems are to be avoided.

4.2 Device Characteristics

As explained in (3) the actual power transferred to the generation and transmission system depends on the detailed (second/second) distribution of power in the wave system modified by the device response and by limits and non-linearities imposed by the operational and control characteristics of the generation and transmission equipment itself. At the present only some of the information on which to base the estimates of the transferred power is available and care has to be exercised in its interpretation.

Each of the device teams (which for the purpose of progressing this study has included the CEGB) have been producing 'efficiency' curves. These are, more accurately, linear response characteristics obtained from model tests or theory for small amplitude monochromatic waves.

Salter has published (5) a large quantity of data in his first year report and the particular response characteristics selected for the TAG 6 assessment were his 'preferred' 'smart' and 'non smart' results dated 24.9.75. for D0015. These are Figure 25 of (5) and reproduced as Figure 2 here. The results apply to fixed centre duck motions and are not radically different from the more recently available 2nd year results with D0018 and the effect of changes in 'damping factors' and 'velocity responses' for more recent models are easily estimated. The damping factor (referred to a 10 cm duck x 30 cm wide) has been taken to be 2.65 N cm r^{-1} s for D0015 and the peak response of the 10 cm duck was noted to be at 1.5 Hz. These quantities will be referred to again under 'scaling'. (Appendix I).

At the start of the TAG 6 study, the best raft results available were those obtained by the CEGB in their Hythe trials - Figure 3 curve a - and these have been used in this study. These results were obtained in a wide tank using a five pontoon string. Subsequent trials with three pontoons showed a marginal improvement (curve b), both tests showing a peak response > 100% normalised to the generated wave and demonstrating the diffraction process quoted by Evans (7). Later tests in the narrower tanks at BHC by both CEGB and recently by Wave Power Ltd., with their better controlled model, confirm the Figure 3 results except that in a 2-D configuration the peak efficiency is about 80%. The output from the 3 pontoon string is, at optimum, fairly evenly divided between the first and second hinges (8), the applied famping factor for a 0.8 m long x 2.44 m wide module was taken to be 400 Nm r^{-1} s (from the early trials) and the peak response occurred at $\sim$ 0.61 Hz. These results were obtained using a moored floating raft string, a realistic operating configuration, but results are again only available for linear (velocity proportional) loads.

The NEL Oscillating Water Column response characteristics have been taken to be the better of the asymmetric can results, Figure 4. These were obtained by NEL from a fixed device with a 10 cm plate spacing and are 'wave to air' conversion efficiencies. There is a shortage of information on this device but this has not unduly limited TAG 6 since NEL made it quite clear from the outset that they were in the best position to design the air turbines for the OWC and we have not seen fit to duplicate this work.

No characteristics are available for the H.R.S. Rectifier. Again this is not important since generation and transmission is conceptually simpler for this device.

4.3 Selection of a Representative Set of Full Scale Device Parameters

With the model tests above being undertaken at different scales and their performances being presented in slightly different ways, it was necessary for TAG 6 to put all the devices on a common basis for analysis.

Theoretical studies within the CEGB (6), (9), (10) and (11) have established scaling parameters, also produced by the Edinburgh team, have produced detailed estimates of device behaviour (including extremes which will be valuable for the stage II study) and especially have rigorised the interpretation of 1-D model tests to full scale 'efficiency' in a sea way. These studies are summarised in Appendix I.

These studies, together with a first order estimate of the overall economics, suggested that a device scaled for a peak sea efficiency in the range $7.0 \text{ s} < T_z < 7.5 \text{ s}$ would be appropriate and this led to the selection of:

(a) Ducks - 20 m diameter

(b) Pontoons of unit length 30 m

and (c) OWC internal plate spacing 16 m.

The sea efficiencies for these devices are shown on Figure 5.

At this scale, full size 'velocity proportional damping values' from which drive torques can be determined were:

(d) $K_{duck} = 10^7 \text{ Nm r}^{-1} \text{ s}$ per m width

(e) $K_{raft} = 1.3 \times 10^8 \text{ Nm r}^{-1} \text{ s}$ per m width

The analysis of extremes, velocity distributions are in Figure 7, and the effect of limiting the generating capacity in the device, Figure 6, led to the additional assumptions of:

(f) Peak (instantaneous) Power $\sim$ 200 kW m^{-1} to achieve a maximum average output of $\sim$ 90 kW m^{-1} which will be restricted to 50 kW m^{-1} to achieve a high load factor.

(g) Maximum offloaded duck angular velocity $\sim$ 1 rad s^{-1} at a probability of 10^{-2}.

(h) Maximum offloaded front pontoon angular velocity $\sim$ 0.35 rad s^{-1} at a probability of 10^{-9}. (1 rad s^{-1} is at a probability of $< 10^{-15}$).

In view of the feelings of the device teams, a further assumption was made:

(i) Linear load characteristics will be preferred but, in the assessment, the same (model) performance would be assumed for all load characteristics.

4.4 Swell

A consequence of the study of means and extremes, A1.2.3., is that swell could be a particularly valuable source of energy to any wave power system with a moderately sized device. Close attention to the estimation of the swell content of the wave climate is therefore urged on TAG 2.

5. SPECIFIC COMPONENT STUDIES

In this section, the studies of specific items of plant for their suitability for wave power application are summarised. These studies were undertaken in parallel (with each other as well as the more detailed aspects of Appendix I) and are not always presented on exactly the same basis. Equally it is not possible to order the separate studies and cross referencing will be forward as often as backward.

5.1 First Mechanical Connection

5.1.1 General - non-hydraulic systems

The preliminary study (1) indicated that except in the case of the OWC/Air turbine system a mechanical connection between the device and the first stage converter was essential, whether or not an increase of speed was involved. GEC Whetstone have carried out a comprehensive survey of possible non-hydraulic connections and examined them for their ability to transmit the peak torques from a wave power device over a long life, (15, 16). These have been followed by specific studies of systems for Ducks (17, 22) and Rafts (18,19). The 'Rubber Tyre' proposals by SEA have been the subject of a separate study (20), (21), (26) by GEC and IRD and a composite TAG 6 view has now been prepared for circulation to Salter/SEA (42).

The initial overview (15) identified the main requirements of the mechanical connection - it must operate with reversing loads in the marine environment for long periods without attention, be simple and for preference be a proven engineering systems. The main contenders were seen to be chains, belts, friction drives, gears and crank and connecting rod assemblies.

The SEA rubber tyres already referred to were not originally included because the unanimous Group view was that the operation of mechanical components, including hydraulic components, in an unmaintainable under (sea) water location was to be avoided if at all possible. Physical considerations made a form of gearing seem the most appropriate to the duck with crank/connecting rod systems totally unsuitable because of the capsize requirement for this device. For a raft, even though the power is distributed between the hinges, the torque loading on each hinge is significantly higher than for the equivalent duck but, in principle, all the options were open to this device.

The more detailed examinations (16) took the most severe torque loading as the design criterion, the Cockerell raft transferring 100 kW/m at one hinge, some 3 MN m/m width of device.

Cranks and connecting rods are shown to be capable of transferring this torque but require most of the available width to do so. Both roller and journal bearings are suitable in the crank pin, the pressure lubricated journal being marginally preferred on reliability and failure mode considerations.

The important point to emphasise is the requirement for pressure fed oil lubrication to achieve the load transfer with good reliability.

Gear drives are also shown to be capable of transmitting the required torque, but again the emphasis is on good design which includes not only the gear form and, especially, close tolerances on centre spacing, but also on the need for a good lubrication system. There is no possibility of sensibly priced sea water lubricated gears with a significant working life. Interestingly, backlash problems do not seem to be as serious as might first be thought since firstly, inertial loadings could be kept down to as little as 10% of the design torque loading and, despite the high frequency of load reversal, this did not seem to be a limiting factor in the design and secondly lost motions are adequately small (17). These last factors will of course have to be examined against specific designs.

None of the other options seem capable of transferring the required torque. Belts cannot be operated with any slack because of the reversing loads but equally when tensioned their load carrying capacity is reduced. Low life due to high rates of wear is the limiting factor and belts cannot compete with gears. Roller chains suffer nearly as much as belts and friction drives (of the roller/ramp type) are limited by very low friction coefficients. The summary statement given in (16) is worth repeating.

Torque Requirement	3 MNm/m
Mechanism Capabilities	
Cranks/connecting rod	3 MNm/m
Gears	0.7 MNm/m (per pinion)
Belts	0.01 MNm/m
Roller chains	0.1 MNm/m
Friction drives	Small

Clearly none of these mechanisms has anything in hand; velocities may be "Victorian but the loads will put the best 20th century engineering to the test. GEC concluded that only cranks and gears were worth examining in more detail although later stages of a speed increasing train, when torque loadings are lower, could make some of the alternatives relatively more attractive. The particular arrangements which emerged from this survey are gear drives for the Salter duck (17), (22) and both gear and crank drives for rafts (18), (19). These are discussed in 5.2.1 and 5.2.2.

5.1.2 General hydraulic systems

In parallel with the GEC study, Lucas undertook a comprehensive survey of possible ways of incorporating low speed hydraulic systems as the primary load for each of the devices (23). This particular survey concentrated on the use of hydraulic rams which are capable of extracting power from the devices without speed increase. These were seen to be particularly suited to the marine environment because of their simplicity (although a large number will be required) their ability to handle a low speed reciprocating input, the ease of combining their outputs at a storage/generation point which can be removed from the sea environment with relative ease, and known reliability. Lucas did not foresee any major problems in 'marinising' the rams, having identified ways in which the rubbing surfaces can be fully isolated from the sea water, though reliability could be a problem.

The declared targets for a suitable WEC ram takeoff were (a) a working pressure of 15 MN m^{-2} (2000 lbf/in^2); (b) no flexible hosing in either HP or LP lines; (c) to take full advantage of the hydraulic interface between WEC and, say, electrical generator by keeping the major control functions within the hydraulics, and (d) pressure throughout the circuit should exceed ambient. On the question of control, two levels are possible, the first will be a necessary sea state to sea state (infrequent) change of, say, the way in which rams are combined and the number of generators in use and the second is to provide almost continuous control to provide the optimum load characteristics to the WEC. The latter raise complex reliability questions and TAG 6 have elected to concentrate on the former in the first instance while allowing that subsequent detailed system improvements are possible.

The study of ways of incorporating rams in the various devices showed that only radial or axial arrangements, Figures 8b, 8c, operated off a cam form, show promise for the Salter duck, the axial one being preferred because neither do the rams contribute to the main bearing load, nor would failed rams give rise to either a radial or an axial load imbalance. The cranked arrangement, Figure 8a, is ruled out because it limits the duck stroke but suffers other major problems which would reduce reliability too. The rams can be accommodated in the duck but side loads on the rams and the rolling contacts on the cam track need careful evaluation.

Space restrictions could make the axial and radial arrangements, Figures 9b, 9c, less attractive for the Cockerell rafts and it is possible but not conclusive, that cranked arrangements will be preferred, Figure 9a. In this device the ram is not required to operate under water but on the disadvantage side flexible hoses or rotary couplings are required in the hydraulic lines and if the ram stroke is designed, as it will have to be, for extreme raft motions, it will not in general be well utilised. Possible ways of overcoming the latter problem by having a variable crank radius, by jacking a moving fulcrum, have been identified but not evaluated. Mechanisms of this type would also enable the ram to be effectively decoupled for maintenance or replacement.

Lucas have also considered ways in which the OWC concept could employ low speed hydraulics (23) in the event that the air turbine approach proves to be unsuitable. Figures 10a and 10b show two examples which involve an additional structure (float or plate) to couple with the oscillatory water surface. These do not look promising and it is recommended that they be 'filed for future reference' should the need arise along with many other arrangements of this type.

In terms of the mechanical coupling of the rams to the device, so long as a sufficient number share the load, both the cam form and crank designs are feasible; in the latter context the analysis by GEC (16) is particularly pertinent.

5.2 Speed Increasing Systems

Faster is smaller, is the rule for either an electrical machine or an hydraulic pump, and the initial studies by IRD (24) and GEC (25) suggested that at least 75 rpm and preferably 100+ rpm should be the aim for electrical generators at their rated output. Two approaches are possible, mechanical and hydraulic. GEC have made specific studies of 'conventional' gear trains to achieve 100 rpm at full rated output for both the Salter duck (17) and the Cockerell raft (18) and have proposed a novel alternative gear system to increase the design margins (22). This was aimed specifically at the duck but could equally be applied to the raft. No special study of 'hydraulic' gearing has been made since a pump/motor combination (without storage) is well known to be capable of speed increase or decrease over a very wide range limited only by the availability of suitable pumps and motors. The hydraulic approach is less efficient than would be tolerable in a gear designed for a long low maintenance life, but the difference may not be too significant. Importantly both gearing and directly coupled hydraulic speed changing will give rise to a motion at the output which ranges from full speed to zero in each wave period and will transmit the final generator load characteristics back to the WEC without modification. The hydraulic approach would in general give rise to a unidirectional motor drive and be more amenable to large speed increases both of which could prove to be advantageous.

5.2.1 Gear drives for the Salter duck

The GEC assessment (17) meets the 100+ rpm design requirement with an overall gear up ratio of 81 : 1 in two stages of 9 : 1. The design is for a 20 m long x 20 m diameter duck with a ring gear at each end which is assumed to have a maximum diameter of about 18 m after allowing for a reasonable thickness of duck. The limiting factor on the design of both stages of the gear train is pinion wear and the torque limits for each stage were balanced to give a near optimum design. Despite the gears being very large, wheel and pinion pcds of 15.3 and 1.7 m on the first stage with a face width of 1.5 m and even 4.5 m, 0.5 m and 0.5 m respectively on the second stage, a total of six sets are required at each end of the duck, equally spaced around the ring gears, to transmit the full load allowing a factor of safety of about 2.5. Not only are the gears massive but a rough assessment of duck bearings and seal requirements (the gears must operate in a carefully controlled environment) suggest that a large ring seal and the radial and thrust bearings will occupy about 4.5 m of duck length at each end and the roughly scaled sketch of this scheme, Figure 11, clearly shows how much space will be taken up by such a gear drive. The effect is not only on the length but also gives rise to a large reduction in the structural diameter of the spine - down to about 6 m. This caused TAG 6 great concern and the sensitivity of the torque capacity of this gear design to increased spine diameter was checked (see 17) which showed that up to 8 m there was no loss of torque capacity but that it was down to 50% by 10 m and 20% by 12 m. A single stage gear, for which each pinion is only some 20 cm diameter, would have been feasible but for the fact that the large diameter ring gear, which is well outside present engineering experience, will almost certainly have to be made in segments and since each segment must be large enough to transmit power over the full swing of the duck (about $\pm$ .28 radians at 200 kW m^{-1}) without a pinion crossing a joint under load, only 11 pinions can be fitted at each end and have an inadequate torque capacity.

Since from the spine diameter viewpoint the single stage of gearing is highly desirable, GEC examined ways in which the 'joint crossing' restriction could be relaxed. The result was the 'guided pinion' proposal (22). Arguing that whilst it might be possible to assemble a large ring gear with accurate control over tooth spacing across each joint but that it would be impossible to achieve a truly circular concentric ring, the major problem was to allow some radial movement in the pinions controlled by the ring gear so as to maintain a constant centre spacing. The concept is shown on Figure 12, and, by now allowing for up to 140 pinions at each end, the original safety factor of 2 is re-achieved without severely restricting the spine diameter. A consequence of this concept, however, is that with such a large number of drives there will either have to be a mechanical or a hydraulic interconnection before feeding power to an electrical generator - 280 x 14 kW generators per duck would cause major problems with interconnection, reliability and routine maintenance. It is finally worth re-emphasising that a factor of safety of only 2 is achieved by using either two sets of 6 bulky two stage drives or 280 guided pinions with pressure lubrication of gears and bearings operating in air sealed from the sea environment. There is no easy solution and many engineers will be unhappy at the prospect of either approach.

5.2.2 Gear drives for the Cockerell raft

A similar analysis (18) for the Cockerell raft presented a different set of problems. First of all the lower device velocity gave rise to a need for a larger overall ratio, 1 : 233, starting from a larger initial torque. Secondly the comparatively shallow draft of the raft makes it more difficult to accommodate a large diameter first stage wheel which also increases the tooth loads. GEC produced a possible design with ten sets of three stage gears across the width of the raft. Although capable of transmitting the required loads, these are very bulky, distort the raft profile and require between 1/3rd and 1/2 of the length of a pontoon. The gear sets, raft bearings and seals would effectively occupy the entire width of the raft. It will be interesting to see if the shape distortion affects raft performance and it is hoped that Wave Power Ltd., will be able to conduct some fairly simple experiments to check this although we understand that the present Wave Power Ltd., design concept would accommodate the gears more easily having a greater overall depth.

5.2.3 Hydraulic rams for ducks and rafts

With the gear solutions possible but so close to the limits of engineering credibility, GEC turned to cranked drives which are mainly appropriate to use with hydraulic rams and an alternative to the cam track ram drive GEC (19) concentrated on a crank driven ram drive for raft applications, it not being suited to the duck. Lucas assessed axial rams for the duck (23).

The raft design, taking note of the large proportion of time when motions are small, produced a requirement for a series of ten beams 3.5 m long, each driving a matrix of 81 rams with a large stroke to diameter ratio of 15 : 1. Compared with the gear drive this makes a relatively compact assembly possible, Figure 13, which can accommodate raft excursions up to the full power rating, incorporates a traditional mechanism for producing a straight line motion. There is plenty of space for steady bearings on the shaft carrying the beams and beam end bearing designs are well within acceptable limits and, furthermore, the drive system would only require one half of the total raft width. The major difficulties are in the area of extreme motions. The extreme design velocity of 0.35 rad s^{-1}, section 4.3, implies raft motions of approximately $\pm$ .6 radians. This could not be accommodated and GEC believe that the only practical solution would be to provide resilient motion limiting stops on the drive shaft carrying the beams with a slipping clutch at the outboard ends to allow the large pontoon excursions. This is a severe limitation to the credibility of this type of ram design and will have to be examined more closely as will the implications of the variable stroke of the rams in operation.

The axial ram/cam form design has the relative merits of allowing continuous rotation of the duck about the spine and always utilising the full stroke of the ram. The side load limitations, rolling contact and possible sea water operation problems have already been noted. For their reference design Lucas (23) chose a 15 m long duck with a peak rating of 3 MW. For this a total of 250 rams just over 9 cm diameter was required, operating on a 14 m pcd and delivering hydraulic fluid at .2 m^3 s^{-1}, 15 MN m^{-2} (44 gals/s at 2175 psi). The design limited the rolling contact load to about 10 tonne and allows the rams to be fitted into a narrow (1 ram + clearances) annulus between duck and spine and, with the reservations already declared, must rate as one of the more promising design concepts particularly if one notes the potential for development by achieving more compact arrangements of rams in multiple stacks (radially) and in series along the length of a duck (or width of a raft). Furthermore, if large diameter seals capable of keeping gears out of the sea water can be economically designed then they could equally be applied to the ram/cam form system. This would reduce the main design problems significantly and replace them with a relatively more straightforward cooling problem.

5.2.4 Rubber Tyres

Having been made aware that SEA, having themselves assessed the alternatives, favoured a dual purpose power take off/duck bearing system using rubber tyres running on the inside of the duck, this was made the subject of a separate assessment.

Using the design criteria set for this study, GEC produced an analysis (26) with a gear ratio of 81 : 1 and a 0.22 m diameter tyre. This led to a clearly impractical requirement for 3420 tyres and contrasts with the SEA proposal for 48 tyres. Subsequent assessment jointly with SEA (20) concluded that a minimum of 77 tyres was required, the reduction from 3420 being entirely explained by a different set of operating assumptions and a change of tyre materials. Further views on the limitations of tyres were formed by IRD (21) and Lucas commented on the proposed hydraulic motors and proposed suspension system. A composite paper (42) has now been prepared and is being sent to Salter/SEA for their comment in which it is concluded that at least 200 tyres will be required if tyre heating limits are to be satisfied even assuming a uniform distribution of load carrying between the tyres.

In all TAG 6 are not happy with this approach believing that it will be difficult to engineer 200 tyres into the duck and are particularly concerned by the Dunlop view that the material proposed, Duthane, will absorb sea water to the extent that tyre life would be limited to 1½ to 2 years and that total replacement at this frequency would not be acceptable.

The composite paper (42) directs specific questions to Salter/SEA which need to be answered as part of a justification to continuing with the rubber tyre approach.

An interesting consequence of the dialogue with SEA is that the loads associated with hydraulic take off systems can be substantially smaller than TAG 6 has assumed, with little loss of performance. This needs to be verified of course but, if it is, this fact would greatly assist the design of gears and cam driven rams in the same proportion.

5.3 Electric Generators

The system options, Figure 1, include electrical machines in three effective groups. Directly coupled machines operating at device speed, directly coupled machines driven via a speed increasing 'gear box' and machines driven by hydraulic motors, fed from local storage, at either fixed speed or within a fairly narrow speed range.

The first two categories have the potential of providing the preferred velocity proportional damping load for the device, being more efficient, and conceivably cheaper, than the pumps, hydraulic motors and fixed speed generators. The difficulties arise from the operation of each generator over a full, reversing, speed range and the need to combine individual generator outputs into a common transmission line (individual transmission to an end user from each generator rated at the maximum allowed by the mechanical connection is not a credible alternative). The final alternative group is conceptually far simpler - most of the control problems being concentrated in the hydraulic circuits - but not without its problems. A very comprehensive summary of all machine types is given in (30).

5.3.1 Directly driven machines - no speed increase

This category of generator, AC or DC, was the easiest to dismiss of any plant item in the study. The direct electrical loading of the 'nodding' motion of the duck or raft was examined by IRD and costed in some detail in (28). A copper cost of £84/peak kW coupled with a mass of iron sufficient to sink either the raft or the duck, made it quite clear that although in the machine sense this was a technically feasible approach, it was utterly impractical. The unsuitability of a linear motion generator for the Cockerell raft was if anything more marked, and ungeared generator systems were eliminated from the study.

5.3.2 Directly driven machines - with speed increase

Having discounted the device speed machine IRD undertook a simple sensitivity analysis (24) from which they concluded that the minimum speed at which the generator should achieve its full output should be 75 rpm and that each doubling of speed would halve the machine volume and significantly reduce the cost. Similar conclusions reported by GEC (25) suggested that 100 rpm be a good target figure and, fairly arbitrarily, this was adopted for direct drive machine and gearing studies.

IRD proceeded to examine the alternative types of electrical machine, their excitation and inter-connection for use in the conversion of wave energy with respect to different load characteristics and the form of the input drive.

Induction generators were eliminated because of control, compensation, and stability problems (30) while permanent magnet machines are considered only economically and technically practical if Alnico permanent magnet material is used. However, such machines, for high ratings (> 1 MW), will be susceptible to demagnetisation while, by definition, the permanent magnet makes excitation control impossible (24). The study has therefore been concentrated on AC synchronous type alternators and DC generators and the problems of interconnecting them.

Fully compensated, separately excited,DC machines, whilst naturally producing the ideal velocity proportional torque loading when delivering power into a resistive load are not suitable for interconnection and bulk transmission. Parallel arrangements are ruled out because the generating voltage of a DC machine is low at typically 1 kV and series arrangements which could give reasonable transmission voltages result in the system current flowing through all the machines which does not enable the ideal load characteristics to be maintained, gives rise to large losses in the system, and will cause the cable at the ends of the series connected line to be at the full transmission voltage, which if it is not to be limited to 22 kV an unacceptably low level for bulk transmission, will require flexible cabling to and from the device way beyond present day practice. The fully compensated DC machine feeding into a load local on the device is the only possible application but depends on alternative transmission media than electricity being economically viable - hot water, produced by resistance heating, and hydrogen are two that have been examined. (The hot water route was also the subject of a GEC study (29)). As will be seen in a later section neither of these transmission options is particularly attractive and the outstanding problems which would have to be tackled, especially of commutator flashover under overspeed (storm) conditions are now probably only of academic interest.

Directly driven AC synchronous type alternators can also be used with individual transmission to a load directly to a resistance heater and through rectifiers to an electrolyser, but again this is only a practical proposition when local loads are involved and the dependence on the viability of the associated transmission system rules out this approach. Compared with the DC machine, even, the AC machine exhibits damping factor variations of approximately 40% due to variations in its internal power factor with load current. This further limitation is compensated to a large extent by the characteristics of an electrolyser when hydrogen production is the choice and a close approximation to velocity proportional damping is possible - but for the present again of academic interest only.

The only feasible approach to the direct generation of electricity which can be coupled to the grid is to combine the outputs of AC synchronous type alternators in parallel through controlled rectifier banks into a short DC link maintained at constant voltage by the inverter (30), Figure 14. The scheme relies on the belief that a line of devices of reasonable length (up to, say, 200 MW or 4 km) can provide a sufficient set of random uncorrelated outputs that the sum output is constant. Given that, and it needs to be checked (to see how frequently and by what extent this condition is not satisfied), a number of other advantages arise:

(a) Although in general the torque/speed curve for this machine is not the ideal linear relationship, it would be possible to control the current flowing in the machine to achieve a very close approximation to the ideal load characteristics;

(b) either no, or a negligible amount of, energy storage between the WEC and the alternator would be required;

(c) individual alternator transformers could be eliminated;

(d) no mechanical rectification to unidirectional rotation would be required,and

(e) single thyristor-device rectifier and inverter units could be used.

As ever, the scheme has its disadvantages, the major ones are that with a direct gear drive the maximum power on each generator would be 600 kW (for the 2 stage duck and 3 stage raft gear systems) and the guided pinion approach with one generator/pinion would only allow a rating of 14 kW, which would present almost insuperable problems of machine interconnection. Neither does direct gearing allow the generator to be decoupled from the WEC so that the generator has to be designed mechanically to withstand substantial overspeeds for which inertial loads referred back to the gears could also be significant. It would be possible to introduce a clutch but this is an undesirable complication and a source of poor reliability. Each of these disadvantages could be minimised by using hydraulic gearing (without accumulators) when it is immediately possible to combine the output of one duck or one pontoon string into a single larger generator of up to 6 MW peak rating, subject to the availability of a suitable hydraulic motor.

A further benefit could be derived from the small phase difference between pontoon hinge outputs and similar, more substantial hydraulic smoothing would be possible by interconnecting a number of ducks. This last is already a feature of the current proposed SEA design (as explained to Ian Glendenning when visiting Lanchester Polytechnic with TAG 3) and would lead to a reduction in the magnitude of velocity swings experienced by the alternators and their installed rating. It remains to be seen whether the loss of WEC performance due to non-ideal load characteristics can justify the apparent complication and probable expense of the direct drive approach. If hydraulic loads can be as effective then one of the indirect generating systems will be preferred.

5.3.3 'Fixed speed alternators' - with hydraulic drive

If the 'constant torque' type of load characteristic of an hydraulic pump with accumulator storage, or of a long hydraulically interconnected system, gives an acceptable WEC conversion efficiency two modes of generator operation are likely. Firstly, if there is a very large storage capacity, capable of smoothing the output from every sea state, the alternators can be operated steadily at 'constant' speed for long periods (while sea conditions remain steady).

This is the simplest of all wave power generator configurations both from the design and the operational point of view and was the one selected by GEC (Hirst) from their analysis of transmission systems (32). The second mode of operation is that required of the approach to output management using a smaller storage capacity which involves switching in or out a number of small 'constant speed' generators to match supply and demand, proposed by Lucas (34).

Both schemes have the real advantage that the machine design can be optimised with a free choice of speed, subject only to the limitations of available hydraulic motors, and especially that the machine need only be rated for a continuous duty at the maximum rms output of the WEC rather than for the peak output and a maximum overspeed of 4 or more times that at the peak rated output. In neither case is speed literally constant but variations can be kept to within, say, ± 10% by control of the hydraulic system pressure.

The GEC scheme (32) summarised in (33) is closest to conventional generating practice in that as few as one alternator per WEC, rated at 1.0 to 2.0 MW is operated at constant speed and power in any given wave state. It is not synchronised with any other alternator, the output being transformed and rectified and connected in series with other devices at DC. Because the store size is proposed to be large enough to fully smooth each wave state controlled changes in power flow take place at the rate of change of the average wave conditions, i.e. over tens of minutes to tens of hours. The control system to effect these changes is conceptually simple and each machine can be isolated hydraulically and electrically for inspection and maintenance. The principal disadvantages of this approach are the large size of energy store needed to fully smooth the WEC output and complications on the hydraulic side necessary to drive the generator at fixed speed over a wide range of output power levels.

The Lucas approach presumes simpler hydraulics and accommodates changes in power level by switching a number of small motor/alternator sets in and out. The study (34) of this system in operation examined the worst case, providing a stepwise continuous output from a single WEC with its own dedicated store and the concept would benefit from the hydraulic interconnection of spaced WECs. From the machine viewpoint this approach has all the advantages and the disadvantages of the GEC proposal but shows a saving on energy store size. It is however, more complicated to control, uses a large number of small connected electrical machines giving rise to problems of synchronising, load sharing, and local instabilities and, for finally supplying a smooth output from a string of WECs, relies on the summation of their individual outputs producing a constant nett power.

It is appropriate to note at this point that, aside from the direct usage schemes, producing hydrogen etc., three preferred alternator systems have emerged. All employ synchronous type alternators in sizes up to 2 MW and, although they seem different, one directly coupled and the others 'fixed' speed with hydraulic drive, they are basically similar differing in the manner in which the multiple WEC outputs are combined to give a smooth output. The IRD approach achieves it entirely on the electrical side, the GEC is entirely in the hydraulics and the Lucas a hybrid. TAG 6 has not been able to select a single technically 'correct' approach since there is still not enough information on WEC/system performance to make that judgement. These three schemes have so much in common, however, that we feel that a sufficient narrowing of the field has been achieved. One particularly important lesson learnt from the Lucas study is the significance of alternator rating, store size and motor generator control philosophy on the efficiency of secondary conversion. This study is described in section 6.

5.3.4 OWCs and HRS rectifiers

The preceding sections have described systems aimed at converting duck/pontoon power to usable electricity since these seem to be the most difficult of the four device concepts - assuming that NEL achieve their declared objective of providing a mechanical output at a shaft rotating in one direction at constant speed.

IRD have been maintaining contact with NEL throughout the TAG 6 first stage study and several points which could affect NEL's thinking have arisen. The first point was that rectification of the oscillating air flow either by valving or in the turbine is essential since the inertia of the generator combines with the low speed characteristics of low pressure air turbines to produce a poor turbine response and loss of conversion efficiency (31). The effect would be particularly marked in small to modest wave conditions when wave periods and the available air flows are smallest. Even having rectified the air flow some questions remain. The maintenance of a relatively fixed speed at the air turbine/alternator implies either continuous matching of the machine load to the input power or substantial inbuilt smoothing either from the interconnection of a number of widely spaced OWC chambers prior to a connection to an electric machine or substantial flywheel storage. Since typical open circuit field winding time constants are of the order 5 s (31) load matching cannot be contemplated on a continuous,wave to wave, basis. If a flywheel is used, which has sufficient inertia to supply power at the mean level over several calm wave periods, it seems likely to have a poor response to the periods of significant input - particularly when starting from rest or when the air turbine is operating at well off design speed such as when it is pumping instead of acting as a turbine. It may well be possible to design round these problems but,of the alternatives,interconnection as low pressure air does not look attractive because of the very low energy densities and a more attractive option may be to use a low inertia hydraulic pump on each column and interconnect a line of WECs into one of the systems described in 5.3.3.

The HRS Rectifier really is the simplest device from the generation and transmission viewpoint, especially in its in shore sea bed standing configuration. The very low hydraulic heads available, presumably no more than 2 to 3 m under full output conditions and substantially less in moderately calm seas mean that turbines will be very large and low speed even compared with designs for tidal barrages. The output will however be fairly even and alternators will be able to operate conventionally at fixed speed. As with all the other devices it will not in general be sensible to contemplate synchronisation direct onto the UK grid and a DC link may be required allowing the option of an alternator running at turbine speed or gearing the turbine output to a higher speed. When sited close to the mainland it could be possible to synchronise the HRS rectifier with the grid.

5.4 Transmission to Shore

In this section the full range of transmission options will be examined, electricity, hydrogen, hydraulic fluid and heat.

5.4.1 Electrical transmission

As pointed out by GEC (32) it is not really sensible to consider transmission systems in isolation, since most of the difficulties arise in the interconnection of device outputs and control. Some general points are worth noting however. It is presumed that the initial low power WEC outputs will be progressively grouped into a main supertension transmission cable, and that since transmission costs reduce as the voltage increases, it would be economically advantageous to achieve the maximum grouping as early as possible in the transmission chain. This also has the advantage that a minimum of the transmission system need be rated for peaks. Except in the case of the HRS rectifier, however, the power source, the WEC, is not a stable structure at a fixed position in space, and any power take off must be via flexible cable. At the present time the upper limit on insulation for flexible cabling is for 22 kV and the maximum rating of the order of 10 MVA (35). This is too small to take the average power from a line of sufficient length to give a smooth output and except when substantial hydraulic smoothing or averaging is provided the cable rating must take peaks into account. In the extreme 10 MVA would perhaps only serve 50 m of device were it not for the fact that transmission cable is more tolerant of short duration overloads than other equipment. It does mean, however, that unless significant cable developments are made it will not be possible to arrange for all the equipment up to main transmission voltages to be mounted on the WEC (the NEL device is particularly suited for this) because the power could not subsequently be taken off. There must, therefore, be a large number of low power flexible feeders to substations on off shore platforms, the sea bed, or on shore. A long duck string with total smoothing in the hydraulics will need a cable at least every 200 m.

For the main transmission cable to shore HVDC is preferable to AC since it makes better use of the copper conductor (32). Since there is a clear need to allow the WEC alternators to vary their speed even in the best smoothed scheme, it will not be possible to think of the alternators operating synchronously with the grid and a DC link will in any case be required and, as is shown in (32) when synchronous alternators are employed the natural place for this link is the main WEC to shore transmission line. It will be seen that the only exception to this is the totally electrically interconnected system postulated by IRD for which AC main transmission is probably necessary. Other general requirements arise from the problem of connecting into the UK grid. A note by CEGB (36) suggests that the appropriate controllable module size is 100 to 250 MW and that the short duration power variations on a 1000 MW installation should not exceed ± 50 MW/15 s if special additional storage plant on the grid is to be avoided, a criterion against which the statistical averaging of power from distributed systems and the minimum storage requirement can be assessed.

It has so far been assumed in this report that any storage will be in the hydraulics aboard the WEC. Some of the alternatives, capacitive, inductive, and inertial were considered in (32) but shown to be bulky and therefore expensive options. If, for whatever reason, the preferred approach to load smoothing is to be the statistical averaging of the outputs from a long line of WECs is the final preferred design, but there is a residual ripple which is too large to meet the ± 50 MW/15 s condition, then off WEC storage would be required. There is as yet insufficient data for such a requirement to be assessed.

The GEC study (32) also considers alternatives to traditional cable designs, for example the use of multicore cables for transmission to shore from each individual WEC so as to minimise at sea equipment. This is shown to be impractical as are superconducting cables in this context.

Each design associated with the three preferred alternator configurations (5.3.3) has a requirement for a substation between the WEC and the main transmission line. If this is to be on a platform, the high cost of the platform makes it necessary for it to serve a very long line of devices which then gives rise to very long low tension, flexible cable runs. The platform is also regarded (32) as vulnerable to collision damage and may not be acceptable for wave power and GEC strongly advocate the design and development of subsea sub-stations which can be distributed along the device line feeding the main WEC to shore transmission cable. It will be necessary that this sub-station be of a simple modular design so that it can easily be maintained by divers - an outrageous concept well worth taking seriously.

5.4.2 Specific Interconnection/Transmission Schemes

A suitable circuit for the direct coupled scheme (30) is shown on Figure 14 (31). The alternators on board each WEC are interconnected at AC and power is transferred to the sea bed sub-station in packages of 1 MW upwards depending on the WEC rating. The output is then put through a short DC link whose voltage is maintained constant by control of the inverter. The inverter outputs are maintained in synchronism with the grid and their outputs paralleled and transformed in two stages onto a new EHV transmission line (to reinforce the grid). It is proposed that each line to shore is rated at approximately 100 MW and that the final step up to 750 kV takes place on shore (Figure 14b). As things stand HVDC transmission to shore could only be possible with a further DC link, the economics of which would depend on the overall cable length and in general may not be worthwhile. The scheme proposed does not fully utilise the flexible cable capacity and it might be better to mount the DC link on the device when it is assembled as a long string and have only transformers on the sea bed.

The scheme for indirectly coupled machines (either proposal so long as the individual alternators in the Lucas proposal are synchronised) is shown in Figure 15 (37). In this case the output from each WEC is either slowly varying or being switched in a controlled manner and is cabled to the sea bed at the largest power level that the WEC can provide within the cable limits. The sea bed sub-station now has one transformer per cable input feeding rectifiers which are series connected to the HVDC transmission to shore. On shore inverters and transformers connect each DC transmission into the grid. This scheme is summarised in (37) and the components described in more detail in (32).

No definitive costs are available but GEC estimate (32) that, excluding cables, the equipment for the indirect scheme should not exceed £100/kW. After including cables for a basic ∿ 20 km transmission to shore, the cost of the grid transforming station and some allowance for a platform on which to mount the seaward end equipment, it is expected that by either method electrical transmission could be achieved for less than £210/kW. This should only be regarded as a 'ball park' figure since, as is explained later in this paper, very few components in these systems are standard and will require working up to a reference design before better cost estimates can be produced.

These costs will depend heavily on the WEC site and the route chosen, and there will in addition be substantial additional costs for grid reinforcement on the mainland. Large power transfers from Scotland to the load centres in England could well cost £90/kW for example. These questions will need to be examined more carefully in the next stage but as a cautionary note, the transmission implications of choosing the Hebridean wave fields for large scale wave power generation (12 GW) are shown on the map, Figure 16, (prepared by DoE/CEGB). 10-20 km off the Hebrides is small compared with the extra ∿ 100 km to the mainland, which will also require underwater cables.

5.4.3 Packaged Electrical Transmission

On the assumption, which is now seen to be wrong, that it would be too costly to meet CEGB supply criteria from remote random power output wave power stations an alternative electrical transmission using battery ships was put forward. As with schemes such as hydrogen transmission, which in the electrolyser/fuel cell combination is also a form of battery transmission, batteries at least offer freedom of WEC siting and freedom to land energy at a convenient site on land. However, the concept was always thought to be unpromising and this was demonstrated in a CEGB study (38). The total battery capacity required to transport power with a reasonable charge/discharge period of 10 h is 100 kWh/kW over a 400 mile sea route from the WEC to the landing point. Ignoring vessel and operating costs, the annual charge for suitable advanced batteries would be no less than £200/annum/kW, which capitalised over the WEC life (if greater than 30 years) is > £2000/kW or about seven times the cost of direct electrical transmission including grid reinforcement to England, and is not therefore an interesting option.

5.4.4 Hydrogen Transmission

IRD have surveyed the possibilities of exploiting wave energy by producing hydrogen at sea and transporting it to shore by pipeline or tanker (39). The arguments in favour include the freedoms of siting WECs and energy landing sites (except for piped hydrogen) mentioned above but also that hydrogen could become a valuable feedstock for fuel substitution in generating plant, transportation and for the chemical industry. Hydrogen, once produced, is also very cheap to store for long periods and could therefore completely eliminate the problems of mismatch between wave energy supply and generating system demand (current estimates used by TAG 6 for the maximum capacity of the CEGB and Scottish Boards for wave power is about 12 GW by the turn of the century). The argument against is only one of cost but it is agreed that the value of hydrogen is difficult to quantify in the absence of a hydrogen based economy. The survey (39) separately costs the elements of the hydrogen producing and transmitting chain.

The favourite production route is to use the rectified output of directly coupled AC machines to electrolyse water at about 30 bar(30). Although an electrolyser is not a purely resistive load, IRD believe that by careful design a close approximation to velocity proportional damping can be obtained with a synchronous alternator/electrolyser combination and as such is a closer approximation to the believed ideal load characteristic than most of the systems considered. In the overall cost exercise, the WEC, gears and alternator were assumed to be £400/kW of average electrical output and the final result is sensitive to this.

Water for the electrolyser has to be either tankered out or produced on board the WEC by desalination. Based on current costs these contribute .08 p/kWh and .004 p/kWh respectively, which capitalises to a mere, say, £3/kW on a 30 year life. The electrolyser itself is a significantly more expensive item and the quoted annual charge capitalises to £170/kW on assumed 1985 technology, it now being noted that each kWh is no longer electrical but thermal energy in the form of hydrogen fuel. The electrolyser efficiency is taken to be as high as 87% for 1985 designs.

Hydrogen produced by the thermochemical means and as hydrogen peroxide were not found to be competitive with the electrolyser approach.

For tankered hydrogen, it was assumed that liquefaction would be necessary at sea and Sulzer have quoted a cost equivalent to £105/kW for a suitable tonnage liquefaction plant. The transport of liquid hydrogen accounts for a further £140/kW and the alternative of gaseous hydrogen pipelines is very much cheaper at £5/kW subsea and £3.5/kW overland for 200 miles in each case. The overall efficiency from electricity at the WEC to landed hydrogen is expected to be between 50 and 60% and the WEC cost has to be increased as the reciprocal of this efficiency when referred to the landed hydrogen.

The cheapest route using desalination and gas pipeline is about £180/kW to which must be added about £650/kW_{th} for the device which at an operating load factor of 70% would deliver hydrogen at 1.4 p/kWh_{th}. The desalination/electrolyse/liquefy and ship route is some £420/kW + £660/kW for the device, or 1.8p/kWh_{th}. In, possibly, more familiar units these are 41 - 53 p/therm. Neither is as cheap a transmission option as the electrical route, although only by a factor of about 2, since the transportation costs on the mainland would be a small addition, but the final cost of the hydrogen is more than four times the cost of fossil fuel. Since the aim is for wave power to be economically competitive and previous analyses suggest that it is marginally possible for electricity produced from wave power compared with that from fossil fuel, the hydrogen route cannot be competitive with the direct generation and transmission of electricity by about the same factor of 4 unless a market for expensive hydrogen is created.

5.4.5 Thermal Transmission

Another feasible system which has some clear advantages. The concept (40) uses a friction brake (which if necessary could be controlled to optimise the load characteristic) to load the WEC, supplying heated fluid through an insulated pipe connection to a floating storage vessel which is one of a set being towed to and from the WEC transporting cold water or oil to the device and returning with hot pressurised water or high temperature oil. The advantages are apparent, simplicity and flexibility. The example analysed is for an oil cooled brake heating water, the transport medium, in a tank standing off from the WEC to 130°C. The tank is sized for 5 days charge/discharge at the maximum continuous rating and GEC estimate that the three tanks needed will cost £90/kW_{th}. No cost estimates are available for the brake itself, the heat exchanges, nor the shore installation, tugs and the cost of operating the system which is liable to be manpower intensive.

The real disadvantage of this and similar proposals is that the final product is water at 130°C. Even if the total cost of the hot water system were only £200/kW and the WEC, not much more than the basic structure, a bare £300/kW, this would seem to be an expensive way to produce hot water. It seems certain that it could not be economically converted to electricity by vapour turbines since even at a 70% annual load factor this modest cost estimate is equivalent to fuel at about 0.9p/$kW_{thermal}$. A cycle based on a flash evaporator would use this thermal energy very inefficienctly, Carnot from 40°C would permit only 10%. The other suggestions such as providing power station preheat would have an extremely limited use (if any) and 0.9p/kWh* is not cheap enough to justify the expense of establishing district heating schemes - also undoubtedly a very limited application in any case.

IRD also considered generating schemes involving the production of hot water/steam when examining for ways of providing an ideal velocity proportion WEC load (41). One obvious way was to use resistance heaters fed from a fully compensated separately excited DC machine to produce water/steam at temperature right up to power station practice if necessary. Again since the best final conversion efficiency would be no more than 30% even under ideal conditions on land, the idea is not attractive.

5.4.6. Hydraulic Transmission

If only, relatively simple, hydraulic components are at the sea end of a wave power system, and all electricity generation takes place on land, then a potentially more reliable, robust and cheap system could result. Lucas therefore examined the possibility of hydraulic interconnection and transmission on a large scale (34).

In first selecting the transmission fluid, filtered sea water was seen to be more attractive than hydraulic oils. First only one pipe circuit is needed and secondly the combination of shorter total pumping distances and lower viscosity makes high pressure water transmission more efficient than the oil alternative. The analysis, based on a 24 km transmission distance using a

* 26p/therm

single circuit 1.22 m diameter pipe, shows that 80 MW could be transmitted at 85% (compared with only 60% for oil transmission). Lucas approached a firm of consultants with North Sea Oil pipeline experience and found that the hydraulic transmission was technically feasible with many of the problems having already been solved in the North Sea. The 1.2 m diameter pipes, a size which will soon be available for the full 15 MN/m^2 pressure, would be concreted over for protection and ballast but it was noted that their use in shallow water (< 50 m) could be hazardous due to cross currents and shipping. Trenching would be essential to give the pipe continuous support and this could prove difficult in the Hebridean region where there is a rock bottom for the most part. Surprising however, was the consultants confidence that a ball jointed 'flexible' riser to connect the WEC to the seabed would not present particular difficulties. The total cost was estimated at £564/kW_{out} but it must be recognised that this only really displaces the cables of the electrical transmission system since the motor/alternator sets will still be required on shore. It was seen to be possible, however, that the electrical interconnection of the individual 80 MW shore units with the grid could be simpler and cheaper than in the all electric schemes and the whole system far more easily maintained and reliable.

In going over the cost breakdown for hydraulic transmission it was noted that the riser assemblies cost only 7 to 8% of the total, and the possibility of flexible hydraulic interconnections between spaced WECs , which had been rejected out of hand at the beginning of the study, was recognised. This is a question which should now be re-examined since the system simplifications which result from statistical averaging could then be available to every device type under review.

5.5 Summary of Transmission Options

For the main transmission to shore, although substantial developments will be required, particularly with subsea sub-stations and the control of a dispersed system of low power alternators, electrical transmission by HVDC from smoothed WEC outputs is preferred. If it is important to precisely maintain velocity proportional damping, an alternative electrical route which does not use storage at the WEC but uses AC main transmission is available as an alternative.

No other transmission type compares with the electrical options on grounds of cost and efficiency but hydraulic transmission is probably the best alternative. It may be shown to be advantageous to combine local hydraulic transmission to interconnect adjacent WECs with a main electrical transmission. Transmission to shore, the basic run of up to 20 km, is expected to cost < £210/kW and on shore grid reinforcement a further £90/kW for Scottish wave fields supplying load centres in the English Midlands. A further cost will be added to all the transmission options except tankered hydrogen, for transferring power from the Hebrides to the mainland.

6. PARAMETRIC STUDY OF A HYDRAULIC/ELECTRIC GENERATING SYSTEM

With a hydraulic drive feeding an accumulator and either a single or a number of switched motor/alternators among the preferred systems, Lucas have examined the operation of such a scheme in detail, using second by second reconstructions of the wave power delivered from the WEC (34). The parameter of particular interest was the choice of hydraulic accumulator size and its effect on conversion efficiency and generator control philosophy.

The system analysed is shown in Figure 17 and the model used a step by step numerical approach. At each time step, after initial conditions were set, the following procedure was carried out:

(i) the instantaneous wave power was calculated, device efficiency was then allowed for to provide a power input to the hydraulic system;

(ii) the power input to the hydraulics was converted to a fluid flow input at system pressure;

(iii) the number of motors in operation was used to calculate the system power output, and the corresponding flow output at system pressure;

(iv) the difference between flow in and flow out gave resultant flow into the accumulator. The content was then updated;

(v) the system pressure was then updated, being directly related to the accumulator content.

This procedure was then repeated over the next time step. The control philosophy adopted for the m/a sets was designed to minimise the frequency of switching. To do this a 'decision period' was established during which the operating conditions (i.e. the number of m/a sets on load) were maintained constant. The duration of each decision period (two minutes) was chosen to allow sufficient waves to pass enabling a realistic pattern to emerge at the end of each decision period. A decision on the number of m/a sets required in the next period was then made. This decision was made by comparing the cumulative energy inputs from the current and previous decision periods and linearly extrapolating into the immediate future. The expected energy input then determined how many m/a sets were required.

More complicated control philosophies might lead to more frequent switching so increasing losses. Although component efficiencies were taken to be 100% throughout, switching losses in the form of energy to accelerate the m/a set and fluid lost before the machine is synchronised were modelled by incurring a penalty for each start up. In addition the extremes of over-pressure and an empty reservoir were covered by including a pressure relief valve and a decision to stop all m/a sets respectively in the model.

The model was tested against 60 minute reconstructions of the six fully developed sea states of Table 1. The first lesson learnt was that 6 x 500 kW alternators/15_m duck incapable of giving sufficiently fine control since too many sea states were unable to even keep one machine operating. 12 x 250 kW sets were subsequently found to be better.

The analysis has served to demonstrate the principle and as can be seen on Figure 18 there is a rapid improvement in efficiency as store size increases up to 8 to 10 m^3 of oil (with an oil : air ratio of 1 : 10) when typically 90% conversion was achieved compared with 60 to 70% at 4 m^3. To put it into perspective, the 10 m^3 store is sufficient to keep one 250 kW alternator running for 10 minutes. As Lucas demonstrate (34) this store (air, oil and oil dump) would occupy only about 12½% of the volume of a duck spine, so is of a very acceptable physical size too.

A number of control decisions were incorrect and better algorithms will need to be developed but TAG 6 are satisfied that technically this approach, even applied to an isolated device, is worth pursuing, and that with hydraulic interconnections between devices the accumulator size could be made smaller without leading to an increased switching frequency or loss of performance. It was also clear from the study that it is overgenerous to rate the motor alternator capacity for the maximum power conditions since too often only one set was in use. Once fully smoothed, although the hydraulics are rated for a full 200 kW/m or thereabouts, the m/a sets need only be rated at possibly 50 kW/m corresponding to 3 sets instead of 12 and a further improvement in minimising the switching frequency could result from using either an increased number of even smaller sets, 8 x 150 kW, say, or a mix of sets of unequal rating. These are typical of a number of detailed options to be examined in the next stage of the study.

7. CONCLUSIONS TO BE DRAWN FROM THE COMPONENT STUDY

Practically all the routes postulated in the system map, Figure 1, have been shown to be technically feasible but in each component area only a small proportion of possible types have been found suitable for use in wave power systems. Considering each area in turn:

7.1 Mechanical Take-Offs

Four mechanical take-offs have been identified as sufficiently promising for further study. GEC summarised the options in (43) starting with four remaining compatible combinations:

(i) geared drive to rotary hydraulic pumps;

(ii) geared drive to electrical generators;

(iii) cam drives to axial hydraulic rams;

(iv) cranked drive to hydraulic rams.

(i) and (ii) incorporate a speed increase whereas the other two effectively do not.

The cranked drive to hydraulic rams, (iv), has one major advantage in that it has a greater torque capacity than the alternative of cam driven rams but does require that the rams operate over a very variable stroke in the wave converter application which would significantly reduce reliability. A larger number of rams are also required and the system has to be protected against extreme excursions. The three remaining systems seem more promising but are not without problems. All require further careful study before they could be clearly distinguished.

A geared drive to rotary pumps (i) has a high 'credibility rating' except that the gears, particularly for the duck, are outside current engineering experience and would require substantial development of both the gearing itself and the machinery to manufacture it. The gears are feasible however and should be very efficient though expensive. Reliability should also be above average.

A geared drive to electrical generators (ii) should also be both efficient and reliable but will again be expensive and subject to the same comments on gears as in (i) above.

A cam drive to hydraulic rams (iii) is the system closest to being available now, but we will have to closely examine the efficiency, particularly at part load, and reliability of this approach. The large number of rubbing seals, the cam track and the rollers on the ram drive rods all require very careful analysis. The prospects of this system operating in sea water are not at all good although it is the only one of the three preferred approaches capable of so doing. The technical problems become far more difficult and inspection and maintenance are impossible.

As a consequence the design of sea water seals to provide watertight machine spaces will be necessary for all the devices.

7.2 Electrical Machines

All the acceptable transmission routes (even the hydraulic route on shore) require synchronous type alternators and the analyses by IRD and GEC indicate that operation at at least 75 rpm at full rated output is required. Device speed machines and all other machine configurations have been rejected. Two basic machine design types will be required.

(i) Machines rated at or around the maximum rms power which operate over a limited speed range from either storage (mechanical or hydraulic) or a hydraulically interconnected line of WECs, and

(ii) Directly coupled machines rated for the instantaneous peak power operating over the full velocity range $\pm$ V max and designed mechanically and electrically for the maximum lifetime overspeed. This overspeed can be held down in hydraulically geared systems.

A large number of detailed questions need to be resolved before machine designs can be finalised and these are set out in (37).

7.3 Generator Drives

For the Salter/Cockerell designs the generator drive is either by direct gearing or by hydraulic motor. This latter configuration may also be appropriate to the OWC but a direct drive from a fixed speed air turbine which incorporates flywheel storage seems more likely (based on discussions between TAG 6 and NEL (44). The HRS rectifier will be expected to directly drive a generator from its turbine but the very low head will tend to make this a very slow machine.

Hydraulic drives will either take the form of simple hydraulic gearing or will incorporate smoothing in an hydraulic accumulator or through hydraulic interconnection of WECs.

7.4 Non-electrical Transmission

All the transmission routes examined have proved to be technically feasible.

(a) Hot Water The transmission of hot water is rejected because (i) there is no identifiable market for hot water as such, and (ii) conversion to electricity is always far too inefficient for the overall scheme to be economic.

(b) Hydrogen The transmission of hydrogen has been shown to be a practicable method of 'getting the power to shore' and IRD's assessment has considered a range of production and transmission methods and estimated an overall cost of landed hydrogen in $p/kWh_{thermal}$. The cheapest route is to electrolyse sea water, desalinated on board the WEC, in a 30 bar filter press electrolyser and transport the hydrogen to shore by pipeline. The equipment costs work out at $\sim$ £180/kW thermal and after adding in a notional device cost £400/kW_e to include the device, mechanical or hydraulic drive to alternators and rectifiers), suitably increased to allow for the overall conversion efficiency of the process, a final cost of landed hydrogen based on a 30 year life is about 1.4 $p/kWh_{thermal}$ (41p/therm).

This approach does not allow the flexibility in WEC siting that the tankered liquid hydrogen route offers but for this the landed cost increases to 1.8p/$kWh_{thermal}$ (53p/therm).

At these prices, the hydrogen is about four times the present cost of fossil fuels and in the absence of a market for bulk hydrogen it is not possible to be certain whether or not this price is attractive. If it were to be converted to electricity in conventional thermal plant, the additional 35% conversion efficiency would make this route unacceptably expensive at 4p to 5p/kWh_e. Furthermore in the light of the remainder of the TAG 6 study it is almost certain that the present estimates are low and it will be necessary to revise them as better structural cost, mechanical/electrical component costs and efficiencies come available. Finally the present cost exercise has not taken account of the additional ocean structures and shore terminals needed to realise the hydrogen route and it is certain that these too would increase costs significantly. No further technical studies seem necessary but costs should be revised as appropriate and kept under review.

(c) Hydraulic Transmission

For bulk transmission of power, hydraulic transmission does not look too promising at £564/$kW_{(hydraulic\ power\ out)}$ over 24 km at 85% efficiency since this strictly only compares with cable costs. It would certainly not be suitable for transmission over greater distances but the possible benefits of hydraulic transmission of keeping all major electrical equipment on shore does justify some further examination of this route. Local hydraulic transmission for WEC interconnection is an attractive possibility worthy of closer examination.

(d) Electrical Transmission

Three basic transmission routes have been identified as technically feasible, packaged transmission is not worth pursuing. The remaining routes are:

(i) nominally fixed speed alternators delivering power via a transformer to series connected rectifiers feeding on HVDC main transmission to shore and on shore inversion and transformation to an EHV line to the UK grid. This route depends on hydraulic or mechanical smoothing on board the WECs.

(ii) Variable speed alternators with its output controlled by a short DC link and HVAC cable transmission to shore. Over long cable submarine routes on HVDC link would be used in place of the AC transmission. This route does not need on WEC smoothing but does depend on statistical averaging on a line of WECs.

(iii) For the HRS rectifier only there is the possibility of synchronous generation with direct transformation onto the grid. Again for long submarine cable routes an HVDC link would be required.

8. THE GENERATION AND TRANSMISSION OPTIONS RETAINED FOR FURTHER TECHNICAL STUDY

The TAG 6 preliminary technical assessment has reduced the very large number of generation transmission options to a very few specific systems which now need to be examined in greater detail.

The remaining "on WEC" equipment options are set out in Figure 19 for each device and are labelled for their suitability for feeding into one of the four remaining transmission systems (not counting hydrogen) which are set out in Figure 20. Hydrogen is not included since TAG 6 believes that a sufficient technical study has been undertaken for the present since there is no identifiable market for bulk hydrogen at ∿41 - 53p/therm.

Figures 19 and 20 merely set out graphically the options described in section 7 but one or two are worth emphasising and some additional comments will be helpful

(i) As so far conceived only transmission route (b), where the alternator is mechanically or hydraulically geared to the WEC, is capable of providing a velocity proportional load. Gears and generators have to be rated for peak powers.

(ii) The combination of hydraulic accumulation/WEC interconnection must be employed for transmission route (a) for which alternator speed variations should be within $\pm$ 10%.

(iii) No speed variation can be tolerated for transmission route (c).

(iv) Transmission route (d) will not be suitable for transmission over great distances.

(v) Figure 16 indicates that for delivering power from the Hebrides an extra 100 km of transmission to the mainland coast will be required. By route (a) this may be any additional length of cable, by route (b) a complete HVDC link will be necessary and by route (d) electricity generation will need to be concentrated on the Hebrides with an HVDC link to the mainland. These are the additional asterisked elements on Figure 20.

The HRS rectifier would use transmission route (a), excluding the flexible cable, under these circumstances.

(vi) Geared electrical drives cannot be used at the 14 kW (guided pinion) level because of the problems of interconnecting a very large number of small unsynchronised machines.

(vii) Other limitations must be expected to arise from further detailed design and cost assessments.

9. COSTS

None of the systems selected can be costed accurately since very few components are standard items; most are therefore specials and some are simply outside current manufacturing experience. Examples of the latter are ring gears and seals for the duck.

However, it was also clear to the TAG 6 members that none of the routes would be particularly cheap and that therefore it was important to make as realistic an estimate of the cost of selected systems as is possible under the circumstances, to enable us to study sensitivities whilst recognising that costs will undoubtedly change as devices, components and systems become better defined.

All four transmission routes on Figure 20 have been costed therefore, the electrical routes including the alternator and additional bulk transmission to the CEGB grid and the hydraulic route,(d), starting with a steady rated sea water pump and finally a land based generating station and bulk transmission to the CEGB grid. The tabulated costings are given in Appendix IV. The method adopted has been to calculate the successive capital cost additions due to each component at its own output rating for a unit input to the alternator/seawater pump taking account of the cummulative system efficiency. The total is normalised to the overall efficiency to give a final cost/output kW.

The following results have been produced, the first cost and efficiency figures referring to a 20 km link to the mainland, and the second set referring to a total transmission of 120 km assumed necessary to land power from the

Hebridean wave field on the Scottish mainland. The routes are identified as in Appendix IV as Ta, Tb, etc., and the table containing the details is shown alongside. The costs presented have been rounded only to the nearest £10/kW so as not to exaggerate differences between the short and long transmission routes.

Routes/electrical

Ta	(i)	£340/kW$_e$	at an efficiency of	77%)	Table A1
	(ii)	£380/kW$_e$	"	77%)	
Tb	(i)	£350/kW$_e$	"	65%)	Table A2
	(ii)	£480/kW$_e$	"	56%)	
Tc	(i)	£350/kW$_e$	"	81%)	Table A3
	(ii)	£450/kW$_e$	"	73%)	

and hydraulic

Td	(i)	£930/kW$_e$	"	62%)	Table A4
	(ii)	£1140/kW$_e$	"	59%)	

in which the route Td(ii) employs HVDC to the mainland with generation on the Hebrides.

Routes Ta, Tb and Tc, excluding alternators and on shore transmission cost £206/kW, £181/kW and £36/kW at 86%, 80% and 95% respectively on the 20 km route.

Since all require mechanical connections and/or hydraulic drives, it would seem that on both cost and efficiency grounds the electrical routes are preferable but the comments on the possible benefits of the hydraulic route in keeping electrical equipment off WEC still stands, since reliability and maintenance considerations will still be key issues.

The next step was to cost a selection of the alternator/sea water pump drives in combination with their appropriate transmission routes. The details are also contained in Appendix IV and the principal routes are summarised below.

(a) Duck/Raft

DR1 Gears with interconnected hydraulic drive to transmission route Ta

20 km route	£1390/kW$_e$ at 61%	)	Table A5
Hebrides	£1430/kW$_e$ at 61%	)	

DR2 Gears with accumulator smoothed drive to transmission route Ta

20 km route	£2940/kW$_e$ at 55%	)	Table A6
Hebrides	£2980/kW$_e$ at 55%	)	

DR2' As DR2 with low cost accumulators

20 km route	£1860/kW$_e$ at 55%	)	Table A6
Hebrides	£1900/kW$_e$ at 55%	)	

DR3 Geared hydraulic, interconnected, drive to sea water pumps Td

20 km route	£2240/kW$_e$ at 49%	)	Table A7
Hebrides	£2520/kW$_e$ at 47%	)	

DR4 Cam driven rams, interconnected hydraulics, transmission route Ta

20 km route	£470/kW$_e$ at 62%	)	Table A8
Hebrides	£610/kW$_e$ at 62%	)	

(or, including raft seals and bearings etc., add £200/kW to DR4 costs).

DP5 Gear drive to alternators and transmission route Tb

20 km	£970/kW	at an efficiency of	64%	Table A9
120 km	£1190/kW	"	55%	

DP6 Hydraulic gearing to alternators and transmission route Tb

20 km	£650/kW	"	53%	Table A10
120 km	£830/kW	"	45%	

(b) OWC

(i) Air turbine direct onto route Ta, i.e. assuming mechanical storage, excluding turbine and storage.

20 km generation and transmission only £340/kW at 77%	See Table A1
Hebrides generation and transmission only £380/kW at 77%	

(c) HRS Rectifier - excluding turbine

(i) Transmission route Tc

20 km £350/kW at 81%	see Table A3
Hebrides £450/kW at 73%	

(ii) Hydraulic intensifier on turbine (excluding turbine) and transmission route Ta

20 km £420/kW at 62%	see Table A11
Hebrides £460/kW at 62%	

The two most expensive routes, DP2 and DP3 are also the least efficient, which introduces a further cost penalty when WEC costs are added in. As explained in Appendix IV the apparent difference between DP1 and DP4, for example, could be covered by the uncertainties in the design and cost of each, particularly with the gears and rating of the cams and rams and rotary pumps. However, these are potentially the cheapest generation and transmission routes for the duck/raft with DP5/DP6 as close second.

Generation and transmission from the OWC and HRS rectifiers are potentially very much cheaper and more efficient. This is important for these devices which tend to be rather larger and less efficient than ducks and rafts. If the alternator cost can, as is anticipated, (AIV 3.3) be reduced the HRS route Tc synchronised onto the grid is particularly attractive.

Total System Plus WEC costs

In order to combine the cost and efficiencies of the various generation and transmission schemes into a single comparable figure, a range of total system costs including WECs have been evaluated (AIV 5). They are presented in Table A12 for a range of device costs of £200 to £800/kW MCR at the input to the particular generation and transmission system. DP2 and DP3 are confirmed as very expensive options costing double the nearest alternative. Converted to a notional generation cost, in p/kWh, over a 30 year life, 70% load factor and 10% test discount rate, DP2 and DP3 would be capable only of generating at 4.3 to 6.9 p/kWh delivered to the CEGB. DP4 on the other hand, seems to have the potential to generate at 1.46 to 3.1 p/kWh. This particular route, using Ta, also shows least bias against the additional transmission from the Hebrides, a mere .07p/kWh or £40/kW.

The other significant point is that the HRS rectifier and OWC systems are significantly cheaper for a given device cost - an additional £200/kW being possible compared with the cheapest duck/pontoon system. The average of the HRS/OWC costs at a WEC cost of £800/kW is almost the same as the average of the duck/pontoon costs at a WEC cost of £200/kW, even excluding DP2 and DP3, which seems significant as an indication of how much more difficult conversion is from the slow cumbersome ducks and rafts. To illuminate the difference further, the notional generating costs from each route for the range of WEC costs is given in Figure 21.

DISCUSSION AND IDENTIFICATION OF SENSITIVE AREAS FROM THE COST STUDIES

(1) The first, and obvious conclusion to be drawn from this cost study is that generation and transmission of wave energy will be expensive.

(2) The detailed breakdown in Appendix IV shows that cable route costs and efficiencies could have a significant impact on the total cost. Cable efficiencies of 0.9 have been assumed, improvements to .95 or more will be very valuable. Cable costs are in general a very small proportion of the total so these improvements should be readily achieved.

(3) The transmission route, Ta, Table A1, would benefit from fully utilising the capacity of flexible cable from the WEC to the sea bed by synchronising up to 10 MVA on the WEC and using transformers and rectifiers at the sea end of the same rating (instead of 1 MVA).

(4) The transmission route Tb, Table A2, is very sensitive to the cost and efficiency of the variable speed alternator which therefore needs careful study.

(5) The main cost in transmission route Tc, Table A3, is the low speed alternator. This has been taken to be £200/kW but is probably high. It is important to establish the operational regime of the HRS rectifier to finalise heads and therefore turbine/alternator rotational speeds so that a machine design can be developed and costed.

(6) The main costs in the duck/raft system, DP1, Table A4, for the gears and the hydraulic pumps. The pumps become expensive because of the need to derate them under normal operating conditions so that they do not overspeed in storms. The need for this derating and ways of avoiding it will have to be examined - the potential benefits are substantial. Gear designs and an assessment of manufacturing techniques and costs are required since reductions on the estimated cost would benefit BP1, DP2, DP3 and DP5.

(7) The DP2 costs, Table A6, are more than double the better routes mainly because of the high cost of the accumulators. There is the possibility of cheaper accumulators (DP2') which must be examined but it is clearly important to minimise accumulation requirements by exploiting 'statistical averaging' to the full. The variance of the sum instantaneous power output from WECs distributed along the line or over an area of sea has to be estimated as a matter of urgency since all the cheaper duck/pontoon routes now depend on a large measure of 'statistical averaging'. This is also of interest to the Salter/SEA team in their assessment of spine stability.

(8) The mechanism for hydraulically interconnecting isolated WECs, e.g. parallel but separate raft strings, needs to be examined bearing in mind the requirement to be able to remove a WEC from the line. The ability to achieve hydraulic interconnection is the key to DP1, DP3 and DP4.

(9) The hydraulic transmission route DP3 is particularly unattractive on cost and efficiency grounds. It needs to be kept in mind but would not seem an appropriate scheme for more detailed study.

(10) A careful study must be made of the cams/rams in DP4/DP6. In particular, their engineering design, behaviour in extreme conditions (raft extreme : MCR velocities are in an even bigger ratio than for the duck) and performance at part load. Cranked ram designs for the pontoon should be re-examined because of the difficulty in achieving the design torque levels.

(11) The OWC generation/transmission route looks particularly attractive - we now need more evidence of the performance to be expected from this device at the air turbine output. If speed cannot be maintained within fairly fine limits with a reasonable inertia we need to know and work up a version of transmission route Tb to suit.

(12) The same comments apply to the HRS rectifier. CEGB studies are looking at possible design hydraulic heads, machine speeds and costs but confirmation will be required from HRS/NEL.

(13) It is clearly important to establish not only the performance of the various WECs, their sizes at full scale and dynamic characteristics but also to determine their relative costs. This will have to be done on a common basis and it may be that the device teams are not in the best position to do this impartially. A joint effort is required by all the TAGs to agree a wave climate, agree device performance figures which they believe could be achieved at full scale, agree structural costs and thence evaluate all the devices in terms of a cost £/kW at an output rating which enables a load factor of, say, 60-70% to be achieved. If this could be carried out early in the TAG 6 stage II study it is possible that a further narrowing of the system choice could be made. It is hoped that the 'consultant study' to be financed by WESC will assist in this analysis.

10. MEETINGS WITH DEVICE TEAMS

As the Stage I study was being finalised, a series of meetings were held with the device teams (except HRS) to inform them of the interim views of TAG 6. At each meeting there were a series of presentations by the participating companies on the work detailed in section 7 of the report. In particular, at each meeting TAG 6 requested information of the device teams needed to progress the study into Stage II. The summary requests are reference (45) and cover:

(1) preferred overall dimensions, method and number of device interconnections;

(2) internal dimensions, form of internal surfaces distribution of ballast/ reinforcement and flexibility of the internal dimensions to suit alternative machine designs;

(3) allowable weight and distribution of equipment;

(4) tolerances in structural assemble;

(5) bearings, seals, planned auxilliary equipment - maintenance arrangements etc.

(6) performance - especially to hydraulic type loads. Identification of non-linear motions;

(7) response of offloaded structure including to extreme and breaking waves;

(8) mooring forces and overall structural movement;

(9) distribution of output (magnitude and phase) from distributed points along a line of WECs;

(10) detailed statistics of velocity, power etc.

TAG 6 volunteered to assist in any of these areas within its competence but with which the device teams may not be able to cope. TAG 6 has also asked (via the Secretary) for the opportunity to be present and even assist in the planned large scale sea trials of model WECs. The members feel that it is important to gain first hand knowledge of the behaviour of devices.

11. RECOMMENDED AREAS FOR FURTHER STUDY BY TAG 6 in STAGE II

The recommended areas of work fall into four basic categories:

(i) continued and extended generic studies;
(ii) system modelling;
(iii) overall costing;
(iv) special device team support/experimental studies.

Each has been discussed within TAG 6 and the participating companies are drawing up proposals to cover all aspects of this work from which it will be possible to formulate a balanced stage II programme. Discussions with Pirelli are taking place on cable aspects of the study because of their experience with submarine cables.

Specifically, in each are:

11.1 Continued and extended generic studies leading to outline design and costing of:

(a) gear configurations for ducks and rafts;
(b) cam driven rams for ducks and rafts and cranked ram drives for rafts;
(c) gear driven pumps for ducks and rafts;
(d) variable speed alternators for gear driven and hydraulically geared generation for use with transmission route Tb;
(e) 'fixed' speed alternators for use with transmission routes Ta and Tc;
(f) hydraulic motor drives for (e);
(g) flexible hydraulics for interconnecting WECS;
(h) specific cable studies:

  (i) LV 'flexible' including terminations which will need to be a 'plug and socket' type at the WEC.

  (ii) Outline investigation of cable routes from specific WEC locations to assess ground conditions, currents, etc. and their effect on cable laying and life.

  (iii) Cable/overhead line routes on the mainland.

(i) modular subsea substation design and the alternative of using an offshore platform for equipment mounting;
(j) studies of equipment for transmission routes Ta, Tb and Tc;
(k) identify and cost auxilliary plant item - lubricating oil pumps, coolers, bilge pumps, etc.
(l) support systems and maintenance equipment, maintenance scheduling, support vessels, dock and harbour facilities. This area will draw heavily on the consultants study;
(m) environmental impacts - fouling and corrosion - on materials selection, seal design and the impact on cost and reliability;

(n) design of large diameter seals;
(o) design of WEC bearings (in consultation with TAG 3).

11.2 System Modelling

(a) Examine system control and stability for each transmission route.

(b) Undertake reliability studies - to include a 'hazard' analysis for each system.

11.3 Total Cost Exercise

(a) Undertake a detailed assessment of overall costs for equivalent WEC systems.

(b) Continue to optimise ratings and operational load factors on the lines proposed in (44).

(c) Update hydrogen route and hydraulic transmission costs.

11.4 Special Support/Experimental Work

(a) Assist in design, construction and instrumentation of Wave Power Ltd. 1/10th scale models.

(b) Continue the joint assessment of 'rubber tyres" with SEA.

(c) Possible environmental tests on seals.

(d) Cable tests - especially flexible cables.

(e) Any of the areas in section 10 of this report with which device teams need assistance.

In addition TAG 6 will continue to provide an advisory/consultancy service for the device teams. This service has been very under-used to date although individual 'product groups' have been approached. It would help if when device teams approach other parts of GEC/LUCAS/IRD and even CEGB/SSEB/NSHB that TAG 6 were to be informed.

Finally, the device teams and other TAGs will be asked to provide information to enable the data base to be improved, in particular:

(1) TAG 2 is urged to pay close attention to the estimation of swell in its wave climatological studies.

(2) TAG 2 could assist in the definition of the statistics of wave power from distributed WECs. The TAG 3 'seakeeping' work will assist in this also as will that by CEGB Marchwood which, being at a more advanced stage of development, has already been used in the stage I study.

(3) Device teams and TAGs should combine to agree a 'basis for comparison' between devices, otherwise there is a danger of WESC being misinformed on the relative merits of devices. The work already undertaken by DoEnergy (44) and CEGB (Appendix I, for example), is a good basis from which to work.

(4) All TAGs and device teams to combine and agree expected full scale size, design rating and WEC cost for each of the device types based on (3) above necessary for detailed TAG 6 design studies. In particular the relative costs and efficiencies of OWC/HRS designs and duck/raft designs need to be determined. A large part of the work of TAG 6 is directed towards the more difficult task of exploiting duck/raft motions which would be inappropriate if these devices are shown to be not competitive on structural cost grounds.

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(12) WESC (GT 10 77).

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(18) WESC (GT 35 76).

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APPENDIX I

THE INTERPRETATION OF MODEL TESTS TO FULL SCALE

In this Appendix a detailed summary of CEGB studies of scaling, detailed performance characteristics (means and extremes) and a method of reconstructing device velocity and hence power output records is presented.

A1.1 Scaling

If we denote the response curves, Figures 2, 3 and 4, as functions of frequency, $\eta(f)$, and require to apply these results to determine the performance of a device at a different scale than the frequency axis has to be scaled as

$$f_{(\text{full size})} = f_{(\text{model})} = \left[\frac{\text{Model Dimension}}{\text{Full Scale Dimension}}\right]^{\frac{1}{2}}$$

so if a 10 cm duck is 80% efficient at 1.5 Hz, one can expect a similarly loaded 10 m diameter duck to be 80% efficient in monochromatic waves of frequency 0.15 Hz etc.

"Similarity' in the load characteristic requires that the velocity response (device velocity amplitude/unit wave amplitude) is the same at each scale. This implies that the applied damping, K, should scale as

$$K_{(\text{full size})} = K_{(\text{model})} = \left[\frac{\text{Full size dimension}}{\text{Scale dimension}}\right]^{7/2} \text{Nm r}^{-1}\text{s}$$

per unit width of device. As an example, since the 0.8 m long pontoon required 400 Nm r^{-1} s/m width, a 30 m wide x 30 m long full size pontoon would need

$$K \text{ full size} = 400 \cdot 30 \cdot \frac{30}{0.8}^{7/2}$$

$$= 3.87 \times 10^9 \text{ Nm r}^{-1} \text{ s}$$

Where required (as for some examples of Salter's duck) 'negative spring' an externally applied buoyancy modifier, scales as $\left[\frac{\text{Device dimension}}{\text{Model dimension}}\right]^3$ and external 'inertial' components scale as $\left[\frac{\text{Device dimension}}{\text{Model dimension}}\right]^4$.

It cannot be overemphasised that the model test results can only be interpreted to full scale if everything is scaled. The effect of duck centre and OWC heave surge and roll motions, the effect of non-linear load characteristics and the hydrodynamic non-linearities introduced by large motions will all modify the predicted full scale performances.

A1.2 Detailed Power Offtake Distributions

Specific statistical studies have been undertaken by the CEGB (9, 10, 11) to assist in the meaningful interpretation of the wave and device information and to give an insight into extreme behaviours. These studies will have a greater impact in Stage II but have already found application for example in the Lucas study of hydraulic storage/generator control (12), and have been used in selecting meaningful peak powers, velocities, etc.

A1.2.1 Sea efficiencies

In order that TAG 6 can choose comparable scales for each of the devices, it is necessary to place them all on a common base. The most meaningful,we think, is an effective conversion efficiency of a device operating in a sea way.

Assuming linearity of response, and the limitations of this assumption have yet to be experimentally demonstrated, the 'sea efficiency' of a device in a given sea is simply the product of the device response and the available power over the full frequency spectrum normalised to the available power, i.e.

$$\text{Sea Efficiency, } \eta_s = \int_f \eta(f).\ P(f)\ df \Big/ \int_f P(f)\ df$$

where P(f) is simply related to the better known 'energy spectral density function', $\varepsilon(f)$, as $P(f) \propto \varepsilon(f)/f$ and since studies by CEGB (12) show that power estimates are not particularly sensitive to the exact form of $\varepsilon(f)$ (from among the standard representations) it is satisfactory to choose one. The Pierson-Moskowitz form preferred in its convenient representation as a function of H_s and T_z, (4) and (10), is

$$\varepsilon(f) = (H_s^2/4\pi T_z^4)\ f^{-5} \exp(-f^{-4}/\pi T_z^4) \quad m^2/Hz.$$

Since H_s only appears as a multiplier on the magnitude of $\varepsilon(f)$, η_s is a function of T_z alone; a result of the linearity assumption. This should be valid for the majority of sea states but not for extremes. A full set of 'sea efficiency' curves are given in (10) covering:

(i) Salter duck: 6 m to 20 m diameter : fixed centre : non 'smart' (DOO 15)

(ii) Salter duck: 6 m to 20 m diameter : fixed centre : 'smart' (DOO 15)

(iii) Cockerell rafts: Unit length, L: 21 m to 48 m: string of three rafts L + L + 2L: Free floating (CEGB tests).

(iv) OWC: Plate spacing 7 m to 28 m: (NEL fixed plate tests).

(v) Salter duck: 10 m to 30 m diameter: single free floating duck: non 'smart' (CEGB theory).

A1.2.2 Full scale dimensions and damping loads

Many factors combine to produce an optimum device dimension. Preliminary studies within the CEGB suggested that the highest operational load factors would be achieved by a device whose peak (sea) response is at $7.0\ s < T_z < 7.5\ s$. This will be achieved by devices of the following approximate dimensions:

(i)/(ii) Ducks 20 m diameter

(iii) Unit pontoon 30 m long

(iv) OWC plate spacing 16 m

(v) Free duck 30 m diameter

The sea efficiencies for these are plotted in Figure 5.

This analysis has highlighted the importance of the string concept to the success of the Salter duck (unless an alternative stabilisation procedure can be devised).

Where it has been necessary, TAG 6 have assumed that full size ducks, rafts and OWCs will have the dimensions listed above. The equivalent full scale applied damping loads, K, can now be estimated from the model data in 4.2 and scaling laws in 4.3.

The 20 m duck will require approximately 10^7 Nm r^{-1} s/m and the 30 m rafts 1.3×10^8 Nm r^{-1} s/m; the difference between these two figures reflecting the much larger velocity response of the duck, the duck's angular movement being some six times greater when producing a given power from the whole device.

A1.2.3 Means and extremes

The first 'mean' of interest is the mean power which the linearly loaded device will transfer from a given sea. Having now derived the 'sea efficiencies', η_s, this is very simple to evaluate (10). The best estimate of the incident wave power using only H_s and T_z is, (13),

$$\bar{P}_{wave} = 0.55\, H_s^2 T_z \text{ kW m}^{-1}$$

and transferred power is on average simply η_s times this. The only exception is that for swell, which is substantially monochromatic,

$$\bar{P}_{wave\ (swell)} = H^2_{swell}\ T_{swell} \text{ kW m}^{-1}$$

and the transferred power is

$$\bar{P}_{out,swell} = \bar{P}_{wave,swell}\ \eta(f) \text{ kW m}^{-1}$$

Since in general $\eta(f) > \eta_s$ for $f = \frac{1}{T_z}$ in the range of interest and since $\bar{P}_{wave}$ is greater for swell than for a wind sea, each of given H_s, it is clear that swell can be a particularly valuable source of power for the moderately sized device. Close attention to the estimation of the swell content of the wave climate is therefore urged on TAG 2.

Having obtained the mean power, in general as

$$\bar{P}_{out,sea} = 0.55\, H_s^2\ T_z\ \eta_s$$

and knowing the scaling damping factor, K, both the mean square velocity, $E(\dot{\theta}^2)$, and the rms torque loading, $\bar{T}$, can be estimated. By definition,

$$E(\dot{\theta}^2) = \bar{P}_{out}/K \ r^2\ s^{-2} ,$$

and the rms torque loading is $(K\ \bar{P}_{out})^{\frac{1}{2}}$.

It was also noted (9) that the distribution of device velocity in a sea way and the mean velocity being zero, the variance of the velocity distribution is also $E(\dot{\theta}^2)$. This simple relationship has made it possible to note the effect of imposing a power output limit on the efficiency of conversion (9,10). A limit of 100 kW m^{-1} would cause a loss of 5% from a 20 kW m^{-1} input, 10% from 29 kW m^{-1}, 20% from 42 kW m^{-1} and 50% from 100 kW m^{-1} so long as the device produced power at 100 km^{-1} when overloaded. If it failed under overload conditions, more severe reductions occur, 18% at 20 kW m^{-1}, 32% at 29 kW m^{-1}, 50% at 42 kW m^{-1} and 80% at 100 kW m^{-1}. The full curves for these two cases are given as Figure 6.

Using the 'limited' case, the CEGB's outline economic studies showed that for the devices already selected in 4.4.2, the upper 'limit' on output peak rating would be 200 kW m^{-1} (with 150 kW m^{-1} probable and 100 kW m^{-1} just possible) and the maximum mean power level landed on shore would be $\sim$ 90 kW m^{-1} (with a restriction to 50 kW m^{-1} most probable on load factor considerations) excluding generation and transmission efficiencies. For the purpose of the TAG 6 study, the 200 kW m^{-1} limit was adopted with the associated peak torque and velocity estimated as explained above.

A further useful piece of 'extreme' information can be deduced from the (known) device velocity response and the (assumed) wave climate, the lifetime distribution of velocity. This is derived from the sum of the Gaussians for each sea state weighted according to the long term wave climate, and was presented in (11). This velocity distribution is quite general and is reproduced in Figure 7. The x-axis carried a scale for both the Salter duck (15 m and 20 m) and the Cockerell Raft (first pontoon motions). The figure has two curves, one is the response of the fully loaded device and the other is the response of the off loaded device in either the failed or protected conditions on the assumption that velocities are approximately doubled through loss of damping. The 100 kW m^{-1}, 200 kW m^{-1} and 300 kW m^{-1} positions are marked on the fully loaded curve and it is clear that if a limit to the instantaneous output power is to be met in this range, the device will be substantially off loaded for between $10^{-1.6}$ and $10^{-2.6}$ of its life.

A probable practical velocity distribution with a progression from the fully loaded to the off loaded curves is also indicated on Figure 7, together with the points (at approximately 1 r s^{-1}) where each device would be expected to capsize. Interestingly the 15 m duck, 'a', could spend as much as 10^{-2} of its life capsized, the 20 m (D0015) duck 10^{-5} and the 30 m pontoon something less than 10^{-15} ($\sim$ 1.5 μs/50 years). At the 10^{-9} design level (an arbitrary choice in common usage, giving $\sim$ 1.6 s/50 years, neither duck will exceed 1.0 r s^{-1} and the pontoon will not exceed .35 r s^{-1} (on the 2 x loaded basis), so both ducks adopt Salter's 'survival' position but the pontoon will not experience a capsize - from which it could not recover. (Breaking waves could be another matter but we have no information as yet).

In the next stage of the TAG 6 study these velocity and derived acceleration and displacement, distributions will be used to examine a full set of machine overload conditions and possible failure modes.

A1.2.4 Reconstruction of records

For some purposes, for example the Lucas studies on accumulator sizing and generator management (12), a continuous record of wave height or instantaneous power, say, is required. Reconstructions of wave elevation are simple enough so long as care is taken to make them aperiodic - a good method for this is given in (13) - but there is no simple correlation of instantaneous power and wave elevation nor of device velocity and wave elevation. Power and device velocity records are, however, just the ones needed by TAG 6.

The technique devised is fully described in (10) and may be of interest to other working groups. It involved splitting the modified power spectral density function ($\varepsilon(f)/f \cdot \eta(f)$) into pass bands of unequal length and evaluating the proportion of the total power from each as

$$\Delta P = \int_{f}^{f+\Delta f} \varepsilon(f)/f \cdot \eta(f)\, df$$

where the pass band is Δf wide and centred on $f + \Delta f/2$. The velocity amplitude for that pass band is then evaluated as

$$\dot{\theta}_a(f+\Delta f/2) = 2\sqrt{\Delta P/K}$$

and since the statistics of velocity are linearly related to the incoming wave, a velocity reconstruction

$$\dot{\theta} = \sum_n \sqrt{\Delta P_n/K}\, \sin\,(\omega_n t + \phi_n)$$

can be produced and, for a linearly loaded device the instantaneous power reconstruction is exactly $K\dot{\theta}^2$.

APPENDIX II

Membership of TAG 6

Chairman:	I. Glendenning	CEGB Marchwood Eng. Laboratories
Secretary:	R.J. Leicester	CEGB Generation Studies, Laud House
	C.O.J. Grove-Palmer/L.A.W. Bedford *	ETSU
	G.A. Goodwin)	Do. Energy
	J.C. Cottrill**)	
	H.H. Heath	GEC Mechanical Engineering Lab Whetstone
	C.J. Peachey	GEC Hirst Research Centre
	R. Potts	I.R.D. Fossway Newcastle upon Tyne.
	J.R. Bumby	" " " " "
	A. Sivill	Lucas Group Research
	J.W.H. Price***	" " "

The following staff of the participating companies made direct contributions and attended some meetings.

P.R. Wyman	GEC Hirst Research Centre
B.E. Morgan	" " " "
D.J. McGee	I.R.D. Fossway Newcastle upon Tyne
M.J. Huyton	Lucas Group Research
N. Lee	" " "
R.E. Blakeley	" " "

* C.O.J. Grove-Palmer and L.A.W. Bedford took over jointly as secretary on 18/2/77. R. Leicester continues as a TAG 6 member.

** J.C. Cottrill replaced G.A. Goodwin on 12/1/77.

*** J.W.H. Price replaced A. Sivill on 24/3/77.

APPENDIX III

PAPERS ISSUED BY THE GENERATION & TRANSMISSION TECHNICAL ADVISORY GROUP TAG 6

WESC (GT.1.76)	Department of Energy CEGB.	WESC 13.1.76.
WESC (GT.2.76)	Wave Power Research Memorandum No. 1 CEGB.	
WESC (GT.3.76)	Getting the Power to Shore CEGB.	WESC (76P57)
WESC (GT.4.76)	Characteristics of the Salter Cam CEGB.	R/M/N 846
WESC (GT.5.76)	The Inverted Can - Some Estimates of Size National Engineering Laboratory.	
WESC (GT.6.76)	Architecture of the Nodding Duck S. Salter et al.	
WESC (GT.7.76)	Progress Report to September 1975 S. Salter.	
WESC (GT.8.76)	Transmission of Electricity from Wave Power Devices H. Whittington.	
WESC (GT.9.76)	Power Characteristics of Wave Power Floats Wave Power Ltd.	
WESC (GT.10.76)	Mechanical Conversion of Random Oscillatory Motion into a Smoothed 50 c/s Electricity Supply Wave Power Ltd.	

WESC (GT.11.76)	Flywheel Power Storage and A Mechanical Infinitely Variable Gear Wave Power Ltd.	
WESC (GT.12.76)	Wave Power CEGB.	RSA Paper R/M/N 879
WESC (GT.13.76)	Proposed Programme on Wave Energy General Aspects Department of Energy.	
WESC (GT.14.76)	First Stage Data Base CEGB.	
WESC (GT.15.76)	Notes on Power Take Off Systems for Salter Ducks and Cockerell Rafts GEC Power Engineering Ltd.	
WESC (GT.16.76)	Power Output From A Wave Power Device CEGB, Marchwood.	
WESC (GT.17.76)	An Assessment of Low Speed Hydraulic Systems for the Extraction of Power From Primary Wave Energy Conversion Device Joseph Lucas Ltd., Group Research Centre.	
WESC (GT.18.76)	Electrical Generators for Wave Energy Conversion Devices GEC Hirst Research Centre.	
WESC (GT.19.76)	An Investigation and Comparison of Different Electrical Schemes for Wave Energy Conversion IRD.	
WESC (GT.20.76)	Low Speed Electrics - Various Motions for Consideration IRD.	
WESC (GT.21.76)	Visit to NEL IRD.	

WESC (GT.22.76)	Bidirectional Motion - Inertia - NEL Device IRD.
WESC (GT.23.76)	Extracting Power from the Waves Using A Nodding Duck Device Without A Speed Increaser IRD.
WESC (GT.24.76)	Design of Low Speed Generators for Salter's Nodding Duck IRD.
WESC (GT.25.76)	Summary of Work to End of September 1976. IRD.
WESC (GT.26.76)	Detailed Power Off-take Distributions I. Glendenning, MEL.
WESC (GT.27.76)	On the Limitations of Some First Mechanical Connexions for Wave Energy Devices H.H. Heath, GEC.
WESC (GT.28.76) (M2)	WESC TAG 6 Meeting Notes R.J. Leicester, CEGB.
WESC (GT.29.76)	Design Considerations of Submarine Power Links A.R.S. Wallace.
WESC (GT.30.76) (M3)	Notes of Meeting at GEC Power Engineering Ltd. R.J. Leicester, CEGB.
WESC (GT.31.76)	Notes on Gear Drives for the Salter Duck H.H. Heath, GEC.
WESC (GT.32.76)	Wave Energy Conversion Progress to November D.J. McGee, IRD.

WESC (GT.33.76) (M4)	Notes of Meeting at IRD Ltd. - 4 November 1976.	R.J. Leicester, CEGB.
WESC (GT.34.76) (M5)	Notes of Meeting at Lucas Ltd. - 9 November 1976.	R.J. Leicester, CEGB.
WESC (GT.35.76)	Notes on A Gear Drive For A Cockerell Raft	H.H. Heath, GEC.
WESC (GT.36.76)	TAG 6 Progress Report to December 1976	I. Glendenning, MEL.
WESC (GT.37.76)	The Electric Transmission of Sea-Wave Energy	B.E. Morgan, GEC.
WESC (GT.38.76)	Power Characteristics for Wave Energy Systems	R.J. Leicester, CEGB.
WESC (GT.1.77)	Some Notes on Interesting Device Parameters	CEGB.
WESC (GT.2.77)	Notes on The Use of Hydraulic Rams for Wave Energy Devices	H.H. Heath, GEC.
WESC (GT.3.77)	Notes relating to Progress on Electrical Machines for Use in Wave Energy Generators	J.R. Bumby, IRD.
WESC (GT.4.77)	Wave Energy Conversion - Economics of the Hydrogen Route	D.J. McGee, IRD.
WESC (GT.5.77)	The Use of Resistance Heaters to Supply Heat to Steam or Gas Turbine Generation Systems.	D.J. McGee, IRD.

WESC (GT.6.77)	The Guided Pinion Concept - A More Powerful First Mechanical Connexion for a Salter Duck H.H. Heath, GEC
WESC (GT.7.77) (M6)	WESC TAG 6 Meeting Notes - 12 January 1977 R.J. Leicester, CEGB
WESC (GT.8.77)	Notes on the Use of Rubber Tyres as a First Mechanical Connection for a Salter Duck H.H. Heath, GEC
WESC (GT.9.77)	Electric Generation & Transmission Applied to Sea Wave Energy and Conversion Dr. C. Peachey & Mr. B. Morgan, GEC
WESC (GT.10.77) (M7)	Analysis of Seaborne Hydroelectric Conversion Systems A.D. Sivill & M.J. Huyton, Lucas Ltd
WESC (GT.11.77)	WESC TAG 6 Meeting Notes - 1 February 1977 R.J. Leicester, CEGB
WESC (GT.12.77)	Hydrogen Route Progress to January 1977 D.J. McGee, IRD
WESC (GT.13.77)	Batteries I. Glendenning, CEGB
WESC (GT.14.77)	Data & Design Information required for 2nd Stage TAG 6 Study for Wavepower Ltd I. Glendenning, CEGB
WESC (GT.14a.77)	Data & Design Information required for 2nd Stage TAG 6 Study for Sea Energy Associates I. Glendenning, CEGB
WESC (GT.14b.77)	Data & Design Information required for 2nd Stage TAG 6 Study for National Engineering Laboratory I. Glendenning, CEGB
WESC (GT.15.77)	Mechanical Power Take-Offs for Wave Energy Devices. A Selection of Systems for Further Study. H.H. Heath, GEC Whetstone
WESC (GT.16 77)	Review of Electrical Machines Dr. J. Bumby, IRD
WESC (GT.17.77)	Storage, Transmission and Use of Wave Energy as a Hot Liquid. P.R. Wyman, GEC Hirst.
WESC (GT.18.77)	Comments on the First Report of TAG 6 to WESC (WESC(76)P110) S.H. Salter, Edimburgh University.

WESC(77)GT 19	Generation and Utilisation of Hydraulic Power M.J. Huyton, Lucas.
WESC(77)GT 20	Work Proposals for Phase 2 of the WESC TAG 6 Study J.W.H. Price, Lucas
WESC(77)GT 21	Further Notes on the number of wheels required for a Salter Duck with friction drive. H.H. Heath, GEC Whetstone.
WESC(77)GT 22	Notes of Tyred Wheels R. Potts, IRD.
WESC(77)GT 23	System Optimisation of Wave Energy J.E.J. Cottrill, DEn.
WESC(77)GT 24 (WPL M1)	Minutes of joint meeting, TAG 6 with Wavepower Ltd on 18th February L.A.W. Bedford, ETSU.
WESC(77)GT 25 (SEA M1)	Minutes of joint meeting, TAG 6 with Sea Energy Associates on 8th March 1977 L.A.W. Bedford, ETSU.
WESC(77)GT 26 (NEL M1)	Minutes of joint meeting, TAG 6 with National Engineering Lab. on 9th March 1977 L.A.W. Bedford, ETSU.
WESC(77)GT 27 (M8)	Minutes of meeting of TAG 6 at GEC Whetstone on 24th March 1977 L.A.W. Bedford, ETSU.
WESC(77)GT 28	Electrical machine configuration for the conversion of sea wave energy J.R. Bumby, IRD and C.J. Peachey, GEC

APPENDIX IV

COST OF GENERATION AND TRANSMISSION SYSTEMS

A IV.1 INTRODUCTION

Having shortlisted a relatively small set of preferred technically feasible generation and transmission routes, it is necessary to estimate their relative costs - in particular to identify particularly sensitive areas. The transmission routes, fig.20, can be costed with reasonable confidence on the basis of the assumptions made for the study. The cost breakdown for each of these transmission routes a to d, designated Ta, Tb, Tc and Td are attached as tables A1,A2,A3 and A4 and are discussed below. The figures given are all 'best' estimates produced after careful consideration by the participating companies and CEGB (Planning Department); THEY CANNOT BE REGARDED AS FIGURES ON WHICH AN ORDER COULD BE BASED. It should be pointed out that the figures on route (c) have not been discussed by TAG 6 and the figures given are those prepared by CEGB Planning Department.

A IV.2 METHOD OF PRESENTATION

The form of presentation seeks to present all costs normalised to a single power rating. It is assumed that each route will have a fixed 'input' power rating from a motor or a pump and where this is derived from storage is taken to be the maximum continuous rating (MCR) but when there is not smoothing (route Tb) this rating is the 'peak' rating, taken to be 4(MCR) which would allow an rms output of .93 rms_{input} at MCR (using fig.6). The first column in each table contains a brief description of the generation and transmission element, the second identifies a probable unit size in the system and the third and fourth columns give the expected unit cost (£/kW output rating) and efficiency of that element. The fifth column gives the 'cost' of including that unit at its expected rating per kW of original mechanical (average) power to the transmission route. This last is the product of the unit cost and the cumulative efficiency up to and including that unit. For example, in route a Table A(1), the LV transformer rectifier and inverter equipment which have a unit cost of £100/kW out have an installed cost of 100 x .95 x .95 = 90.3 £/kW_{in}. A fixed allowance of £50/kW in is included for a 'platform' on which to mount the seaward end of the main transmission. This is only a 'reasoned guess' but is more realistic than any figure which could be put onto distributed submarine substations. In addition to the common components, separate additions are made for the 'short' 20km to mainland, and 'long', 120 km to mainland via the Hebrides, transmission routes. The final totals are an overall efficiency and cost £/kW input which are finally converted to a cost, £/kW of electricity delivered to the CEGB, by simply dividing the input related cost by the efficiency.

Since all the electrical routes include the alternator and on shore transmission to the CEGB, separate estimates of 'transmission to shore only' cost and efficiency, excluding these items, have been made. These are the figures referred to in the text (Sections 5.4.2 and 5.5) for comparison with other transmission only schemes.

A IV.3.1 TRANSMISSION ROUTE a - Ta (FIXED SPEED ALTERNATORS AND HVDC TO SHORE.) TABLE A1

This route is suitable for use with all the devices given that sufficient smoothing has been built into the WEC through storage or hydraulic interconnection. A nominal alternator rating of 1 MVA is assumed at a cost of £20/kW roughly double the cost of large machines. The transformers and rectifiers are assumed also to be rated at 1 MVA and this small size leads to the £100/kW unit cost including the on shore (100 MVA) inverter which services the HVDC transmission from 100 series connected WECs. This approach does not take full advantage of current flexible cable capabilities, 10 MVA, 22kV, and the possibility exists of synchronising small subgroups of alternators - possible being driven from the same hydraulic accumulator or commoning pipeline - into a single flexible cable, transformer and rectifier. This would save an estimated £20/kW in the unit cost of this equipment. The quoted transmission cable efficiencies are also probably low, estimates made by CEGB at Guildford suggest that 99% and 97% for the 20km and 120km routes would be good targets for a 100MVA HVDC transmission.

The overall costs £/kW delivered are £335/kW and £376/kW for the short and long routes respectively at an efficiency of a 77% in each case. If both the transformer rectifier savings and cable efficiency improvements can be achieved, these costs would reduce to £293/kW and £330/kW and the efficiency rises to 86%. The 'transmission only' cost without the improvements, is £206/kW with an efficiency of 86%.

A IV.3.2 TRANSMISSION ROUTE b - Tb (VARIABLE SPEED ALTERNATORS AND HVAC TO SHORE) TABLE A2

The costs for this route, which is aimed mainly at the Salter/Cockerell devices, are inevitably more speculative since the alternator is a very unusual machine, rated on a mixture of a peak power level and an overspeed, which is independent of power and related only to the lifetime distribution of device velocity. It is not yet known which will be limiting and it is not possible to be certain whether the estimated cost and efficiency of these machines is high or low. The same comments on transmission cable efficiency apply, the long route, having two cable efficiencies included in this analysis, being particularly sensitive to underestimates. If 0.97 could be achieved on both AC and DC transmission without an increase in the estimated cable cost almost a £90/kW reduction in the overall cost would be realised and the efficiency of each route would be increased to 70% for the 'short' and 68% for the 'long'.

The 'transmission only' cost, without improvements, is £181/kW at an efficiency of 86% but as estimated the overall costs including alternators and transmission to CEGB are £350/kW at 65% and £476/kW at 56% for the short and long routes respectively.

A IV.3.3 TRANSMISSION ROUTE c - Tc (FIXED SPEED ALTERNATORS SYNCHRONOUS WITH THE GRID.) TABLE A3

This route, in its basic form, is only really suitable for the HRS rectifier on which quite powerful alternators are conceivable, perhaps 10MVA. (This route has only been studied within CEGB). The very low heads available to the turbine on this device lead to the speculation that a directly driven alternator will be a very large open frame or rim type machine and could be very expensive. The £200/kW figure reflects the uncertainty in this area rather than the cost and could well be expected to reduce. In the final cost of £350/kW for the offshore HRS rectifier, the alternator accounts for £222/kW, 63% of the total. Reductions in the alternator cost will therefore be very significant and if realised, together with an overall efficiency of 0.81 must rate as the most attractive route IF the HRS rectifier can be built sufficiently cheaply to take advantage of it.

For transmission from the Hebrides, it would no longer be necessary to operate synchronously with the grid since a HVDC link would be needed for the submarine route. However it could well be possible to operate sets of HRS rectifiers in synchronism with each other to maximise the rating and minimise the cost of the HVDC link. On this basis, transmission from the Hebrides to the CEGB would cost an estimated £445/kW with an efficiency of 73%, the alternators again accounting for a large proportion of the total cost £246/kW out or 55%. The 'transmission to shore' only cost (5km in this case) and efficiency are £36/kW and 95% respectively for the basic off shore route.

A IV.3.4 TRANSMISSION ROUTE d - Td (HYDRAULIC TRANSMISSION WITH ON SHORE ELECTRICITY GENERATION) - TABLE A4

With the hydraulic transmission, there are the alternatives of directly driving sea water pumps at the WEC or using one of the other methods, for example the interconnected hydraulic drive, to power sea water pumps at a 'fixed speed'. Lucas seem to marginally prefer the latter approach because of the cost and difficulty of designing low speed sea water pumps with all their materials problems etc. The route costed, Td, is therefore directly comparable with the first electrical route, Ta, since both require a similar drive. The total cost of the 20km route, at £926/kW at an efficiency of 62% is therefore fairly judged to be almost three times as expensive and 15% less efficient than its electrical competitor. There is a large margin to make up on savings to be achieved through improvements in reliability by keeping major electrical items on shore. Additionally there seems to be little scope for development and cost reduction, North Sea technology already being very advanced through intensive research and massive investments.

The additional cost of 100km of hydraulic pipeline would be out of the question entirely and even the addition of an HVDC link from the Hebrides to the mainland adds a further £220/kW to the cost. The overall figures for hydraulic transmission to the Hebrides with on Hebrides generation and dc transmission to the mainland followed by ac transmission to the grid are £1142/kW and 59% efficiency.

A IV.4 OVERALL SYSTEMS

Unlike the transmission routes, the drives from WEC to alternator cannot be costed with anything like the same confidence since it is in this area, fig.19, that the greatest design and manufacturing uncertainties lie. Three groups have been considered: (a) Duck/Pontoon drives, not distinguished because there is too much uncertainty to do so meaningfully, (b) an OWC drive and (c) two HRS rectifier drives. The same method of presentation is employed as for the transmission routes above and the final item on each drive is the appropriate transmission route.

Several of the routes described below make use of 'hydraulic interconnections'. This assumes that a number of WECs, not necessarily part of a single structure, have their outputs commoned into an accumulator of very much reduced overall size when compared with that required for fully smoothing a single WEC output. The concept should greatly reduce costs but depends on a sufficient 'statistical averaging' being achieved. This is expected but is not yet demonstrated.

Finally, the routes described and costed below are not a complete set but merely a representative set for sensitivity studies and whilst major differences can be indicative of a ranking, differences of £500/kW are well within the levels of uncertainty and should not be regarded as too significant at this stage.

A IV.4.1 GEARED, HYDRAULICALLY INTERCONNECTED DRIVE FROM DUCK OF PONTOON TO Ta - DR1 TABLE A5

In this route, both the gears and the wheelpumps need to be rated for peaks and these, as a result, form the greater part of the overall cost. Although the gears can in principle supply power from 14 kW peak (the guided pinions) to 400 kW peak (the large ring gears for the duck or quadrant gears for the raft), the overspeed requirement on the wheel pumps severely restricts the rating of the pumps and gears at operating speed. The gear cost, £100/kW, is not reliable being a 'ball park' figure arrived at in discussion between GEC (Whetstone) and Davey Loey but not based on a specific design, but is agreed by TAG 6 to be a realistic first guess. The pumps, however, are costed on the basis of a 400kW wheel pump with a maximum speed of 50 rpm which can be purchased in bulk for £5000/unit. In the direct drive situation, gears, hydraulic gears, or even the rubber tyres, this 50rpm speed has to correspond to the design maximum. Over its life, the duck will not exceed $1rs^{-1}$ (fig.7) since this is the velocity at which it overturns but, depending on the size/damping, peak power is produced at a much lower speed, $0.13rs^{-1}$ on the assumptions for this study or $0.29rs^{-1}$ on the data given by Salter/SEA. Working from $0.2rs^{-1}$, an intermediate figure, the peak output from the pump is achieved at 10rpm at which speed the pump is rated at only 95kW. The associated maximum continuous rating for load factor optimisation is about ¼ of this (ie average rating referred to the final smoothed output achieved from a system peaking at 200 kW/m - fig.6) so the machine originally rated at 400kW is operationally only a 24kW machine. This has been rounded down to 20kW for the purpose of this analysis giving a unit cost of £250/kW of rated average output. This twentyfold reduction in machine rating due to the way it is under utilised in a wave power situation is clearly something which has to be examined in greater detail but TAG 6 believed the principle to be correct and would warn device teams against the simple application of 'catalogue' ratings and costs to their own studies. The rating could, however, be significantly increased by careful controls of pressures in the hydraulic lines.

After taking these gear and pump costs, valves, hoses interconnecting lines, and hydraulic motors and coupling with transmission route Ta overall costs of £1390/kW and £1413/kW have been estimates for the short and the long transmission routes respectively with an overall efficiency of 61% in each case. Since the gears and wheel pumps make up about 45% and 25% of these costs respectively they are clearly sensitive areas for closer examination.

A IV.4.2 GEARED HYDRAULIC DRIVE FROM DUCK OR PONTOON WITH $10m^3$ ACCUMULATORS DRIVING TRANSMISSION ROUTE a - DR2 TABLE A6

Lucas arrived at a $10m^3$ (oil) accumulator as the preferred size for fully smoothing on isolated 15m wide WEC and the costing D.R-2 assumes this size.

Gear and wheel pumps are taken to be the same as in DR1, with the same reservations. The surprise in this route is that the pressure accumulators when assembled from existing units of known reliability will cost £1000/kW. By replacing the interconnections of DR1 with these $10m^3$ accumulators, more than £1500/kW out is added to the price making total of £2940/kW and £2980/kW for the short and long route respectively at an overall efficiency of 55% in each case.

A much simpler accumulator design, which has so far only been tested on a laboratory scale and is of unknown reliability has been suggested by ACC-Hydro through GEC. This is expected to cost $\sim$ £250/kW by which means the cost of DR2 can be reduced by more than £1000/kW_o to £1855/kW_o and £1896/kW_o for the short and long routes respectively.

This is still very expensive and clearly whatever improvements can be achieved from detailed gear and pump studies it is important to minimise the hydraulic accumulator requirement by incorporating as wide an hydraulic WEC interconnection system as possible and, since some accumulation is still likely to be needed, to examine the low cost alternative carefully.

A IV.4.3 GEARED INTERCONNECTED HYDRAULICS FROM DUCK OR PONTOON TO HYDRAULIC/ELECTRIC TRANSMISSION d - DR2 TABLE A7

The high cost of hydraulic transmission, particularly for the 'long' route makes this more expensive than DR1 by a factor of about 2 times associated with a reduction by 33% in efficiency. The last factor increases the contribution, to the overall cost, of the WEC by 50%! For the record, the overall costs and efficiencies for long and short routes are £2240/kW at 49% and £2519/kW at 47% respectively. The gear and pump studies could bring these costs down since combined they represent 54-58% of the total, but the effect would not be to make DR3 competitive with the electrical alternatives.

A IV.4.4 CAMS/RAMS AND INTERCONNECTED HYDRAULICS FOR DUCKS OR PONTOONS TO Ta - DR4 TABLE A8

This cost study is on a slightly different basis in that Lucas have prepared an outline design for a raft using 3000 ram pumps, cam tracks etc. for a 50m wide raft. The cost, excluding seals/bearings etc. and assuming an MCR of 50 kWm^{-1} at the input to the rams, reduces to £141/kW. Lucas point out, however, that the design of the device is strongly dependent on the torque requirements and hence scaling from models is important. Only preliminary evaluations of loads on the cam track/rod ends particularly under maximum velocity conditions were made. The estimate is therefore certain to be low.

After adding in interconnections and hydraulic motors and transmission costs Ta, this nevertheless leads to an overall cost of £571/kW at 62% efficiency for the short route and £611/kW at 62% for the long route. Lucas recommend that the bearings and seals for the raft could add a further £140/kW (at MCR) an addition of £204/kW to the above totals. Seal and bearing costs have not been included in the other systems however and without them there is room for the cam/ram system to increase in cost by a factor of 5 before this system has the same estimated cost as DR1.

On the face of it this is the most attractive option so far identified but, with the possibility that the gears and pumps in DR1 could cheapen and the probability that the cams/rams in DR4 will be more expensive, it would not be wise to treat either as particularly more or less promising. Both need more detailed study. The difficulty experienced in achieving the demanded pontoon torque loading suggests that cranked cam drives should be given further careful consideration.

A IV.4.5 GEARED DRIVE FROM DUCKS OR PONTOONS TO ALTERNATORS (Tb)- DR5 TABLE A9

Gear costs are taken to be the same as for DR1 with the same reservations and account for more than half the overall cost. The short and long routes work out at £965/kW at 64% efficiency and £1190/kW at 55% and are on the face of it cheaper than DR1 but will be less sensitive to reductions in estimated gear and (for DR1) pump costs. Note however that this approach is not suitable for the 'guided pinion' and will probably not therefore be suitable for the Duck.

A IV.4.6 HYDRAULIC GEARING FROM DUCKS OR PONTOONS TO ALTERNATORS (Tb) - DR6 TABLE A10

This uses the ram/cam drive of DR4 but with hydraulic motors rated for peak duty of 4 x MCR and achieves a reduction compared with the estimates for DR5 of > £300/kW delivered to the grid. This is, however, accompanied by a drop in efficiency of 10-11%. The final costs and efficiencies are £652/kW at 53% for the short route and £827/kW at 45% for the Hebridean route. The ram/cam cost estimates are of course subject to the same expected upward adjustment as in DR4.

A IV.4.7 OWC AIR TURBINE DRIVING A 'FIXED' SPEED ALTERNATOR ON Ta - OWC1

This route is a direct connection of the OWC turbine to Ta and has the costs and efficiencies of Ta. These are

	20 km to shore	£335/kW at 77%
and	Hebridean route	£376/kW at 77%

If the air turbine performs satisfactorily with mechanical atorage, this is a very credible, high efficiency low cost route - overall very attractive. It must be emphasised that the cost do not include the air turbine and its associated valving or mechanical storage, the equivalent of the first mechanical connections in the Duck/Pontoon routes.

A IV.4.8 LP TURBINE ON HRS RECTIFIER DIRECT TO ROUTE Tc - HRS1

As with the OWC above this is a direct drive onto a transmission route Tc. The costs are £350/kW at 81% efficiency for the short route and £445/kW at 73% efficiency for the Hebridean route. If the turbine speed can be kept fairly high, and open frame generators are employed there seems to be a good chance of substantially reducing these costs which do not include the turbine.

A IV.4.9 HRS RECTIFIER WITH HYDRAULIC DRIVE TO Ta - HRS2 TABLE A11

In the event that turbine speeds are uneconomically low, it would be possible to effect a speed increase with wheel pumps driving wheel motors. Transmission route a would certainly be cheaper than normal because of the shorter cable runs and the fact that no offshore platform is required. The reductions for these are given in brackets in table A11. The costs and efficiencies are

5km offshore £$^{423}_{(348)}$ /kW at 62%

and Hebridean route £$^{464}_{(379)}$ /kW at 62%

The costs are therefore similar to HRS1 but efficiencies are lower.

A IV.5 INCLUSION OF DEVICE COSTS

In the assessment of Hydrogen as a transmission and storage option, it was assumed that a device with mechanical drive and generators would cost £400/kW. at MCR. It can now easily be inferred from, for example, DR4 and Ta, that the cheapest mechanical drive (excluding air turbines and HRS rectifier turbines which have not been examined) is via rams/cams and motors. Their cost with the alternators from Ta are £200/kW so fi £400/kW is realistic it implies a total structural cost of £200/kW, including seal bearings etc., referred to the maximum continuous alternator output rating. This is assumed to be the absolute minimum cost, some £10000/m on a device with a maximum out put of 50kW/m. The total cost is $\left(\frac{\text{device cost}}{\text{system efficiency}} + \text{system cost}\right)$ per output kW at MCR. The values of total cost for each of the systems given in tables A5 - A11 (DR1 - 6, OWC 1, HRS 1 - 2) are given in table A12 for WEC costs of 200, 400, 600 and 800 £/kW at the system input. For the numbers to be comparable the WEC costs must refer to the same load factor. If a nominal 30 year life is assumed a notional generating cost can be found as $\frac{\text{Total cost (£)}}{10 \times 8760} \times \frac{100}{0.7}$ p/kWh, taking the load factor as 0.7 and a discount rate of about 10%;

Nominal generating cost = (1.63 x capital cost x 10^{-3}) p/kWh.

Excepting DR2 and DR3 which are very much more expensive than the alternatives at 4.3 to 8 p/kWh, the other Duck/Pontoon options are in the range 1.46 to 4.47p/kWh.

By contrast the OWC (OWC1 range is 0.97 to 2.3 p/kWh) and the HRS Rectifier (HRS1, 0.97 to 2.5 p/kWh) costs reflect the enormous advantage of the much simpler cheaper and more efficient transmission routes available to these devices by virtue of their continuous and relatively high speed (the OWC much higher than the HRS rectifier) outputs. Either the OWC or the HRS rectifier can cost more than £200/kW more than the equivalent Duck/Pontoon - but it must be remembered that the OWC and HRS WEC cost/efficiency includes the turbine whereas the Duck/Pontoon WEC costs are for the structure, including bearings, seals and machine beds, but no generating equipment. Even so, the average of DR1, 4, 5, 6 is in the range £1301 - 2354/kW, 2.21p to 3.84p/kWh, whilst the range of averages of the OWC and HRS examples is £681 - 1555/kW, only 1.11pto 2.53 p/kWh indicative of the relative difficulty of exploiting the slow motions of the Ducks and Rafts but it is equally clearly essential that the capital cost of the various WEC types be determined as soon as possible - on a common basis such as £/kW out at a rating at fixed lifetime load factor based on, say, the India wave climate. Based on studies by DoEnergy (44) and supported by studies in CEGB a suitable load factor should be in the range 0.6 to 0.7.

Finally, a cautionary note on the interpretation of Tables A12 and fig.21. The common basis on which WEC costs are assumed to have been calculated is

$$\text{WEC cost} = \frac{\text{CAPITAL COST OF WEC (£/m)}}{\text{RATED OUTPUT TO GENERATION AND TRANSMISSION SYSTEM (kW/m)}}$$

Where the rated output has been assumed to be that MCR (kW/m) at which the WEC can operate with an annual load factor of $\sim$ 70%. Based only on general discussions within TAG 6 the OWC and HRS rectifiers, being larger than ducks or rafts, would be expected to have higher capital costs/m and, as far as we know being less efficient, smaller rated outputs at the defined load factor. It might be, therefore, that in comparing ducks/rafts with OWCs/Rectifiers the former could still be cheaper overall despite the greater difficulty and cost of getting their power to shore.

TABLE AI

Ta	TRANSMISSION ROUTE a (Fig. 20) INCLUDING ALTERNATOR AND ADDITIONAL GRID CAPACITY TO MID ENGLAND

Component	Unit Size	Unit Cost (£/kW_{out})	Efficiency %	"Cost" (£/kW_{in})
Alternator ∿ "Fixed" speed	∿ 1 MVA	20	95	19
'Flexible' Cable Link	<10 MVA	7.5	100	7.2
L.V. Transformer	∿ 1 MVA			
Rectifier		100.0*	95	90.3
Inverter (On Shore)	∿100 MVA			
Platform Allowance		50		50
(A) CUMULATIVE TOTALS			90	166.5

ADD - 20 km TO SHORE

Component	Unit Size	Unit Cost (£/kW_{out})	Efficiency %	"Cost" (£/kW_{in})
20 km HVDC Cable	∿100 MVA	8	90**	6.5
Shore Station ***	∿250 MVA	20	100	16
On Shore Transmission to CEGB		90	95	69
(1) TOTALS - INCLUDING (A)			77	258

OR ADD 120 km FROM HEBRIDES

Component	Unit Size	Unit Cost (£/kW_{out})	Efficiency %	"Cost" (£/kW_{in})
120 km HVDC Cable	∿100 MVA	48	90**	39
Shore Station ***	∿250 MVA	20	100	16
On Shore Transmission to CEGB		90	95	69
(11) TOTALS - INCLUDING (A)			77	290

OVERALL COSTS (£/kW DELIVERED TO CEGB) AND EFFICIENCY

(1) 20 km Transmission to Shore £335/kW_{out} @ 77%

(11) Hebridean Route £376/kW_{out} @ 77%

NOTES: * If cables and rectifiers at full 10 MVA, Reduces to £80/kW

** Cable efficiencies taken at <u>MINIMUM</u>

*** Switching and transforming to ehv grid link

(Route (1) excluding alternator /grid link ⇒ £206/kW_e @ 86%)

TABLE A2

Tb	TRANSMISSION ROUTE b (Fig. 20) INCLUDING ALTERNATOR AND ADDITIONAL GRID CAPACITY TO MID ENGLAND

Component	Unit Size	Unit Cost ($£/kW_{out}$)	Efficiency %	'Cost' ($£/kW_{in}$)
Alternator	4 MVA$_{(peak)}$	40 (MCR)	80	32
Rectifier/Inverter	1 MVA (AV)	40	95	34
Flexible Cable Link	1 MVA	7.5	∿ 100	5.7
Transformers	100 MVA	25	100	19
Platform Allowance		50		50
(A) CUMULATIVE TOTALS			76	143
ADD - 20 km TO SHORE				
20 km AC Cable	100 MVA	22	90**	15
Shore Station ***		20	100	14
On Shore Transmission to CEGB		90	95	58.5
(1) TOTALS INCLUDING (A)			65	228
OR ADD 120 km FROM HEBRIDES				
20 km AC Cable	100 MVA	22	90**	15
DC Link (2 ends)(inc***)	250 MVA	47		30.5
+ Small Sub on Hebrides		10	100	7
100 km HVDC Cable	250 MVA	40	90+**	23.4
On Shore Transmission to CEGB		90	95	50
(11) TOTALS INCLUDING (A)			56	267

OVERALL COST £/kW DELIVERED TO CEGB AND EFFICIENCY

(1) 20 km Route to Shore $£350/kW_o$ @ 65%

(11) 120 kM Route $£476/kW_o$ @ 56%

NOTES:
* Takes account of peak : average power ratio ∿ 4:1 at MCR
** Minimum Values Taken
*** Switching and Transforming to EHV Grid Link
+ Includes converter/inverter efficiency

(Route (1) excluding alternators and grid link $£181/kW_o$ @ 86%)

TABLE A.3

Tc	TRANSMISSION ROUTE C (HRS RECTIFIER ONLY)

Component	Unit Size	Unit Cost ($£/kW_{out}$)	Efficiency %	'Cost' ($£/kW_{out}$)
Alternator (Synch with Grid)		200*	90	180
Transformers Etc.	250 MVA	10	100	9
5 km AC Link	250 MVA	5.5	95**	5
Shore Station ***	250 MVA	20	100	17
On Shore Transmission to CEGB		90	95	73
(1) TOTAL -5km TO MAINLAND			81	284

HEBRIDEAN ALTERNATIVE

Alternator		200*	90	180
Transformer Etc. on WEC		10	100	9
105 km HVDC Cable	250 MVA	42	90**	34
DC Link (2 ends)	250 MVA	47	95	36
On Shore Transmission to CEGB		90	95	66
(11) TOTAL - HEBRIDEAN ROUTE			73	325

OVERALL COSTS £/kW DELIVERED TO CEGB GRID AND EFFICIENCY

(1) 5 km WEC to Shore £350/kW @ 81%

(11) Hebrides to Shore £445/kW @ 73%

NOTES: * This is a high estimate assuming very slow alternators - could be reduced after design study.

** Minimum cable efficiencies

*** Switching and transforming to ehv grid link

(Route (1) excluding alternator and grid link ⇒ £36/kW @ 95%)

TABLE A4

Td	TRANSMISSION ROUTE d - HYDRAULIC TRANSMISSION (LUCAS PREFERRED ROUTE*)

Component	Unit Size	Unit Cost ($£/kW_{out}$)	Efficiency %	'Cost' ($£/kW_{in}$)
Sea Water Pumps	< 400 kW	10	90	9
Risers, Manifolds & 24 km Pipe	68 MW	564	85	431
On Shore Generating Plant	∿ 60 MW	100**	85	65
(A) TOTALS TO ELECTRICITY			65	505

WEC 20 km FROM MAINLAND

Shore Station/Grid Connect	250 MVA	20	100	13
On Shore Transmission		90	95	56
(1) TOTAL (20 km) INCLUDING (A)			62	574

HEBRIDEAN ROUTE

HVDC Link (2 ends)	250 MVA	47	95	28
100 km HVDC Cable	250 MVA	40	100	21
Grid Connection		4	100	2
On Shore Transmission		90	95	45
(11) TOTAL HEBRIDEAN ROUTE INCLUDING (A)			59	670

OVERALL COSTS £/kW DELIVERED TO CEGB AND EFFICIENCY

(1) 20 km Route £926/kW_o @ 62%

(11) Hebridean Route £1142/kW_o @ 59%

NOTES: * Lucas estimate that WEC mounted oil hydraulic pumps/motors driving sea water pumps is cheaper than direct sea water pumping.

** CEGB (HQ) estimate for Pelton Wheel based station.

TABLE A5

(a) DUCK/PONTOON DRIVES

DR1	GEARED INTERCONNECTED HYDRAULICS TO

Component	Unit Rating	Unit Cost ($£/kW_{out}$)	Efficiency %	'Cost' ($£/kW_{in}$)
Gears	14-400 kW	100**	98	392
'Wheel Pumps'	20*	250	90	220
Interconnection (5%)		12.5		11
Hoses and Valves (5%)		12.5		11
Hydraulic Motors	< 400 kW	10	90	8
(A) TOTAL TO TRANSMISSION(a)			79	642
+ 20 km Ta(1)		335	77	204
TOTAL WITH Ta(1)			61	846
+ HEBRIDEAN Ta(11)		376	.77	228
TOTAL (HEBRIDES) WITH Ta(11)			61	871

OVERALL COST/kW DELIVERED TO CEGB AND EFFICIENCY

(1) 20 km Route £1390/kW @ 61%

(11) Hebridean Route £1431/kW @ 61%

NOTES: * Rating based on max duck speed = 5 x speed at MCR

** Very very rough estimate of gear prices

TABLE A6 (Duck/Pontoon Drives Contd.)

DR2	AS (1) BUT ACCUMULATORS FOR SMOOTHING

Component	Unit Rating	Unit Cost ($£/kW_{out}$)	Efficiency %	'Cost' ($£/kW_{in}$)
Gears	14-400 kW	100**	88	612
Wheel Pumps	20*	250		11
Accumulator ($10m^3$)	(fully smooth)	1000 (260)	90	794 (206)
Motors	< 400 kW	10	90	7
TOTAL TO TRANSMISSION (a)			71	1424 (836)
TOTAL WITH Ta(1)			55	1607 (1020)
TOTAL WITH Ta(11)			55	1629 (1043)

OVERALL COST/kW DELIVERED TO CEGB AND EFFICIENCY

(1) 20 km Route £2940/kW @ 55%
(£1855)

(11) Hebridean Route £2980/kW @ 55%
(£1896)

NOTES: * Rating based on max duck speed = 5 x speed at MCR

** Very very rough estimate of gear prices

( ) BRACKETS REFER TO POSSIBLE LOW COST HYDRAULIC ACCUMULATOR SYSTEM

TABLE A7 (Ducks/Pontoon Drives Contd.)

DR3	GEARED INTERCONNECTED HYDRAULICS TO (d)

Components	Unit Rating	Unit Cost ($£/kW_{out}$)	Efficiency %	'Cost' ($£/kW_{in}$)
Geared Drive as (1)	<400 kW		79	642
+ 20 km Route (d)		926	62	453
TOTAL - 20 km TO SHORE			49	1095
+ HEBRIDEAN ROUTE (d)		1142	59	532
TOTAL HEBRIDEAN ROUTE			47	1174

OVERALL COST £/kW DELIVERED TO CEGB AND EFFICIENCY

(1) 20 km to shore £2240/kW @ 49%

(11) Hebridean Route £2519/kW @ 47%

TABLE A8

DR4	CAMS/RAMS - INTERCONNECTED TO (a)

Cam Tracks) Rams (3000)) Oil Reservoir) Pipes/Valves)	* £353k/50 m Raft		90	127
Interconnections	(as above			12
Hydraulic Motors		10	90	8
TOTAL TO TRANSMISSION (a)			81	147
ADD TRANSMISSION Ta(1)		335	77 62	209 356
ADD TRANSMISSION Ta(11)		376	77 62	235 382

COST £/kW DELIVERED TO CEGB AND EFFICIENCY

(1) 20 km Route £571/kW @ 62%

(11) Hebridean Route £611/kW @ 62%

NOTE: * Lucas estimate based on available equipment

ADD £204/kW FOR SEALS/BEARINGS ETC.

TABLE A9

DUCK/PONTOON DRIVES (Cont. (11))

DR 5	Geared Drive to Alternator and Tb			
Component	Unit Size	Unit Cost ($£/kW_{out}$) (AVE)	Efficiency %	Cost($£/kW_{in}$) (AVE)
Gears	<600 kW*	100**	98	392
(1) Transmission (b) (1) (20 km)		350	65	223
TOTAL (b) (1)			64	615
(11) Transmission (b) (11) (Hebrides)		476	56	261
TOTAL (b) (11)			55	653

Overall Cost $£/kW_{\text{delivered to CEGB}}$ and efficiency

(1) 20 km to shore. £965/kW @ 64%

(11) Hebridean Route £1190/kW @ 55%

Notes: * 600 kW (Peak) rating on one pinion ie not guided pinion approach.

** Gear costs very uncertain. The estimate used leads to ∿ £700/kW of the total

TABLE A10

DR6	Hydraulic Gearing to Tb			
Component	Unit Size	Unit Cost ($£/kW_{out}$)	Efficiency %	Cost($£/kW_{in}$) (AVE)
Cams/Rams etc. as DP4			90	127
Hydraulic Motors	400 kW (Peak)	10	90	32
TOTAL TO Tb			81	159
(1) Transmission Tb(1)	(20 km)	350	65	184
TOTAL including Tb(1)			53	343
(11) Transmission Tb(11)	(Hebrides)	476	56	216
TOTAL including Tb(11)			45	216

Total Costs(£/kW delivered to CEGB and efficiency

(1) 20 km to shore £652/kW @ 53%

(11) Hebridean Route £827/kW @ 45%

(b) OSCILLATING WATER COLUMN

OWC 1 Preferred Route - Air turbine with mechanical storage - fits directly onto Route (a).

. . Excluding WEC/Turbine and controls,

(1) 20 km to shore, Ta(1), £335/kW_o @ 77%

(11) Hebridean Route, Ta(11),£376/kW_o @ 77%

(c) HRS RECTIFIER

HRS 1 Preferred Route - LP Turbine to transmission route (c)

. . Excluding water turbine

(1) 5 km off shore, Tc(1), £350/kW_o @ 81%

(11) Hebridean Route, Tc(11), £445/kW_o @ 73%

TABLE A11

HRS 2	Hydraulic Intensifier to (a)			
Component	Unit Size	Unit Cost (£/kW_{out})	Efficiency %	Cost (£/kW_{in})
Wheel Pumps	100 kW	50	90	47
Wheel Motor	<400 kW	10	90	8
Drive to Transmission (a)			81	55
20 km, Ta(1),		335 (260)	77	209 (162)
TOTAL			62	264 (217)
Hebridean Route, Ta(11)		376 (291)	77	235 (181)
TOTAL			62	290 (236)

Overall Cost £/$kW_{\text{delivered to CEGB grid}}$ and efficiency

(1) 5 km off shore £423/kW @ 62% (348)

(11) Hebridean Route £464/kW @ 62% (379)

*Note Intensifier only needed for very low speed turbine 100 kW assumes basic 400 kW pump with an operating speed of 12 rpm.

( ) Brackets refer to Ta less platform and most cable.

TABLE A12 TOTAL SYSTEM COSTS FOR A RANGE OF WEC COSTS

DEVICE	SYSTEM		TOTAL SYSTEM COST £/kW$_{\text{to CEGB}}$			
			200 **	400 **	600 **	800 **
(a) Duck/Pontoon	DR1(i)	61	1720	2050	2370	2700
	(ii)	61	1760	2090	2420	2740
	DR2(i)	55	3300	3670	4030	4400
	(ii)	55	3340	3710	4070	4440
	DR2'(i)	55	2220	2580	2950	3310
	(ii)	55	2250	2620	2990	3350
	DR3 (i)	49	2650	3060	3460	3870
	(ii)	47	2950	3370	3800	4220
	DR4(i)	62	890	1220	1540	1860
	(ii)	62	930	1260	1580	1900
	DR5(i)	64	1280	1590	1900	2220
	(ii)	55	1550	1920	2280	2640
	DR6(i)	53	1030	1410	1780	2160
	(ii)	45	1270	1720	2160	2610
(b) OWC	OWC1(i)	77	600	850	1110	1370
	(ii)	77	640	900	1160	1420
(c) HRS Rectifier	HRS1(i)	81	600	840	1090	1340
	(ii)	73	720	990	1270	1540
	HRS2(i)	62	750	1070	1390	1710
	(ii)	62	790	1110	1430	1750
	HRS*2(i)	62	670	990	1320	1640
	(ii)	62	700	1020	1350	1670

(i) Refers to transmission to Mainland over ~ 20 km
(ii) Refers to transmission to Mainland via Hebrides ~ 120 km
HRS*2 reduced by eliminating platform and some cable.
** WEC costs £/kW at input to system - rated at MCR and given load factor
DR2' Assumes reduced accumulator cost.

NOTE: Care must be exercised when interpreting this table to compare different WECS. The WEC costs must be calculated on the same basis set out in AIV.5

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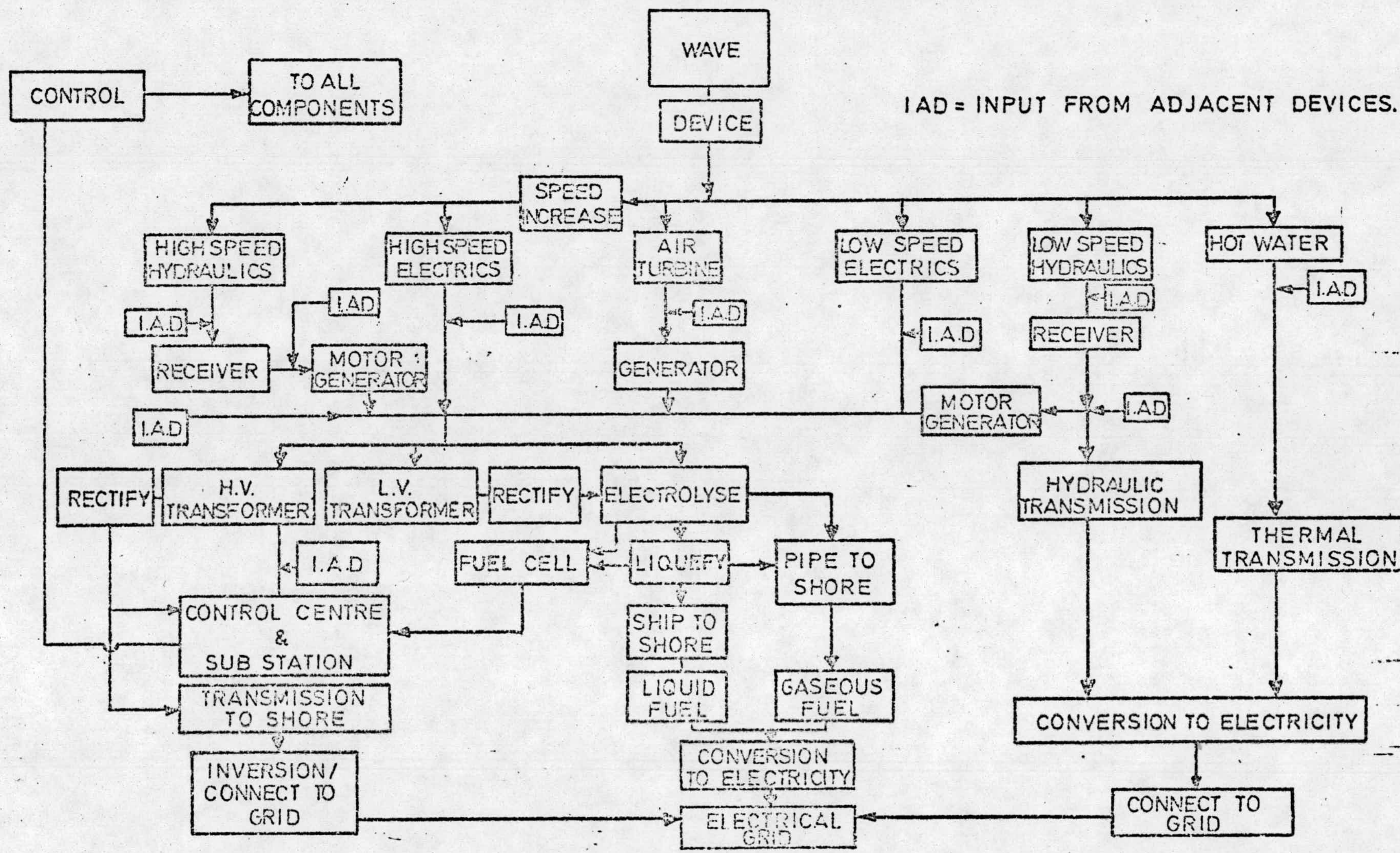


FIG 1 CONCEPTUAL CONVERSION & TRANSMISSION SYSTEMS FOR TAG 6 STUDY

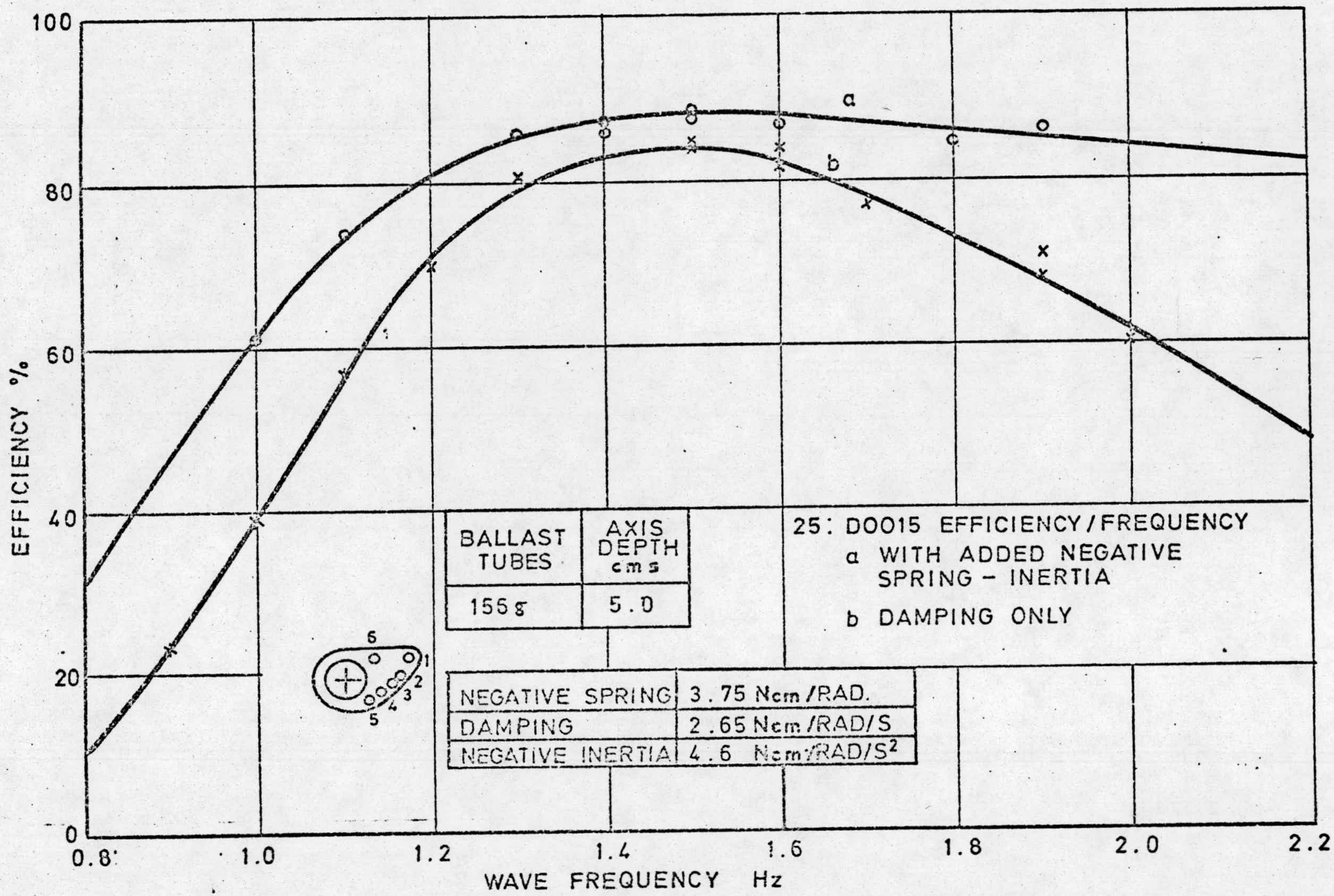


FIG. 2. DUCK EFFICIENCIES (DO015) [SALTER FIRST YEAR REPORT]

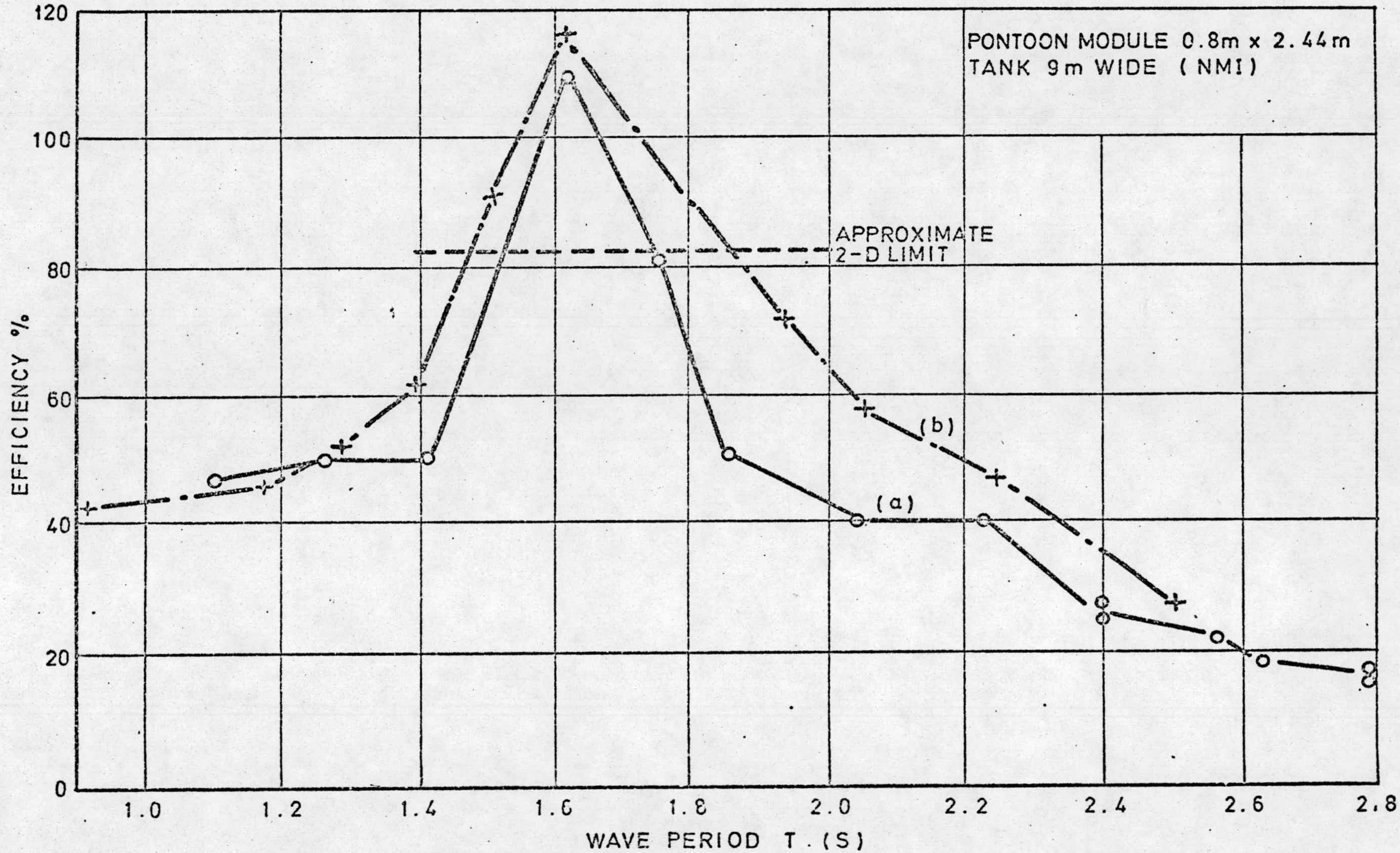


FIG. 3. BANDWIDTH CURVES FOR 5, (a), AND 3, (b), RAFT STRINGS (CEGB)

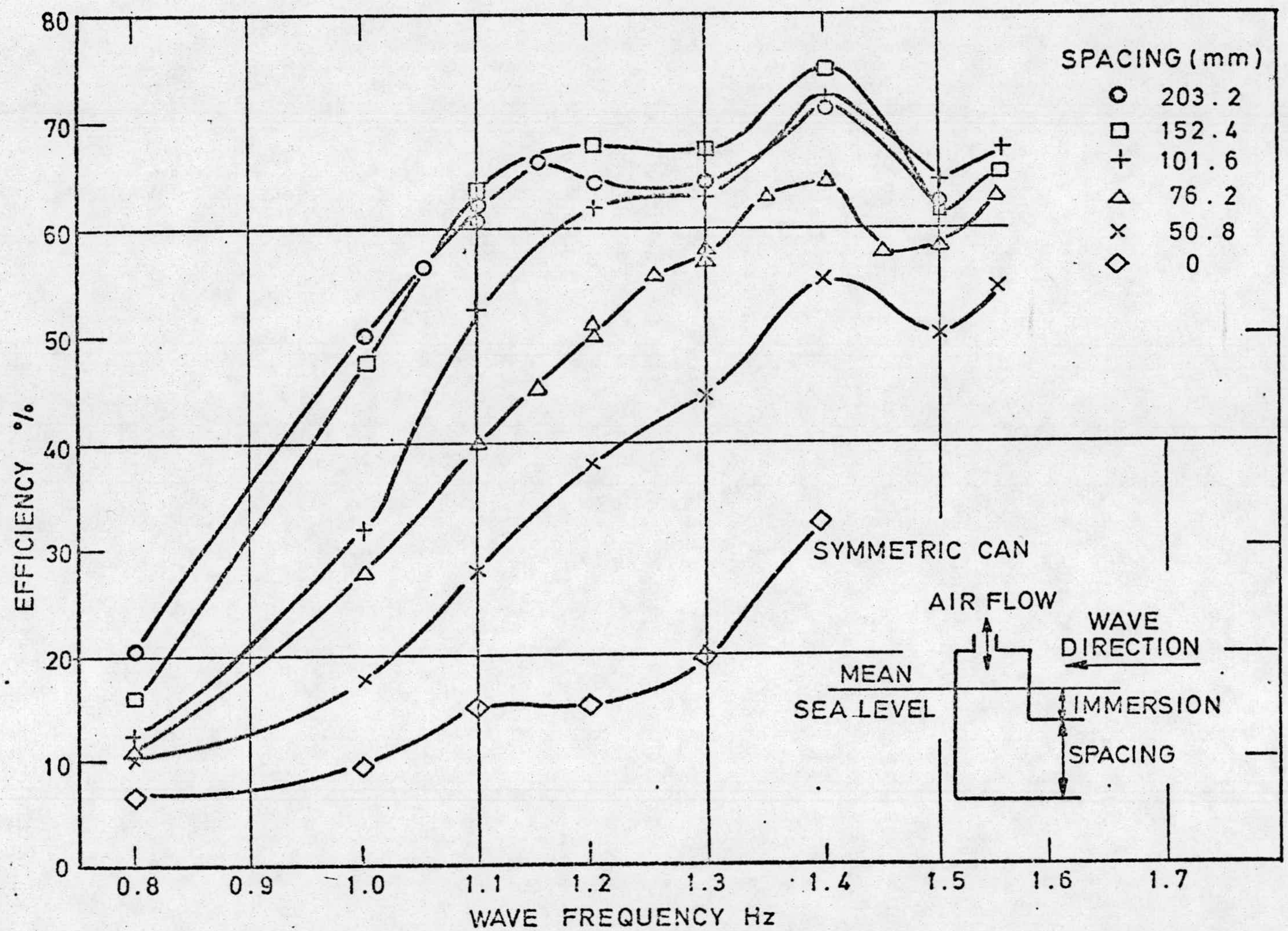


FIG. 4. O.W.C. CONVERSION EFFICIENCY FOR VARIOUS CONFIGURATIONS

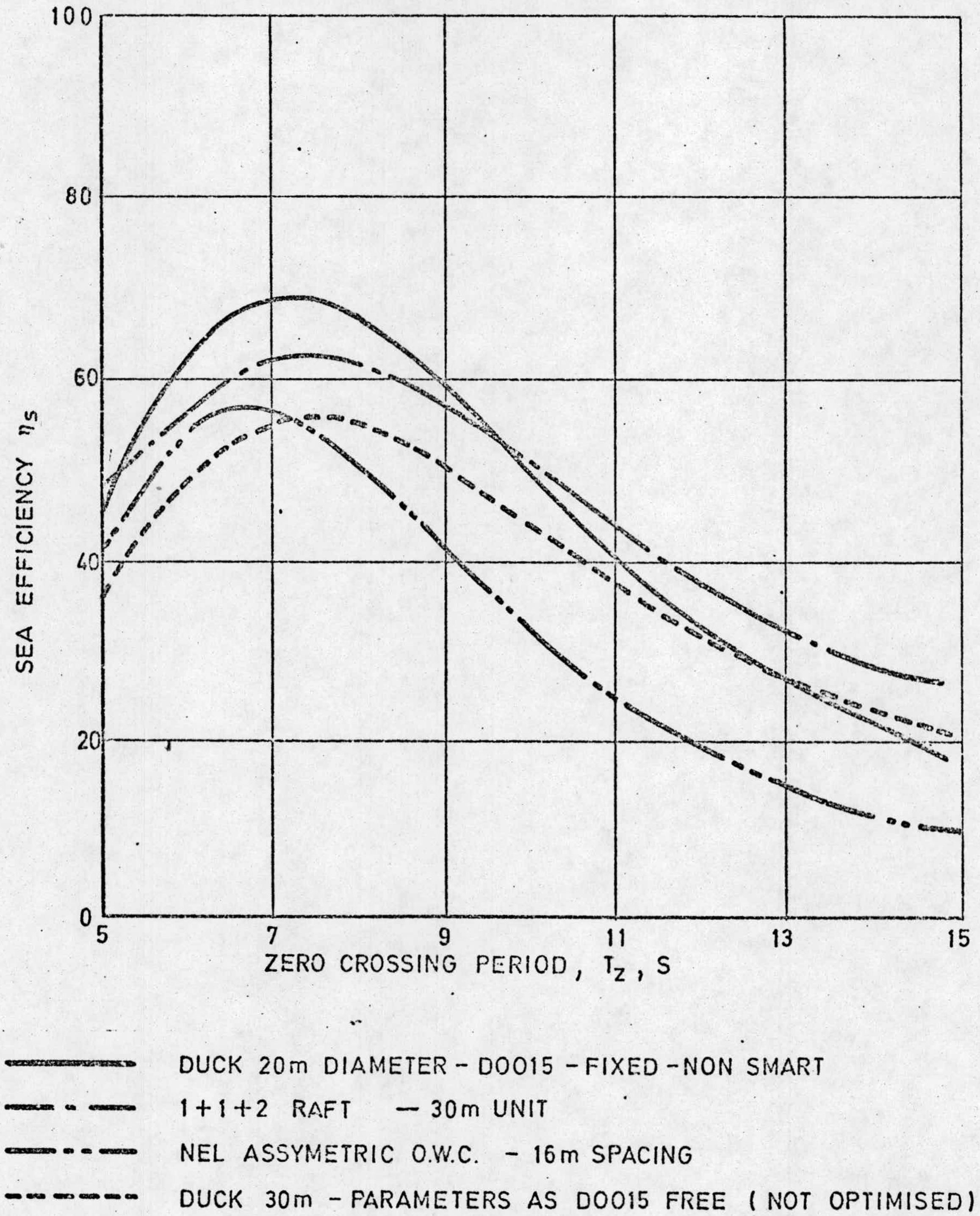


FIG. 5. SEA EFFICIENCIES OF SELECTED SET OF FULL SCALE DEVICES

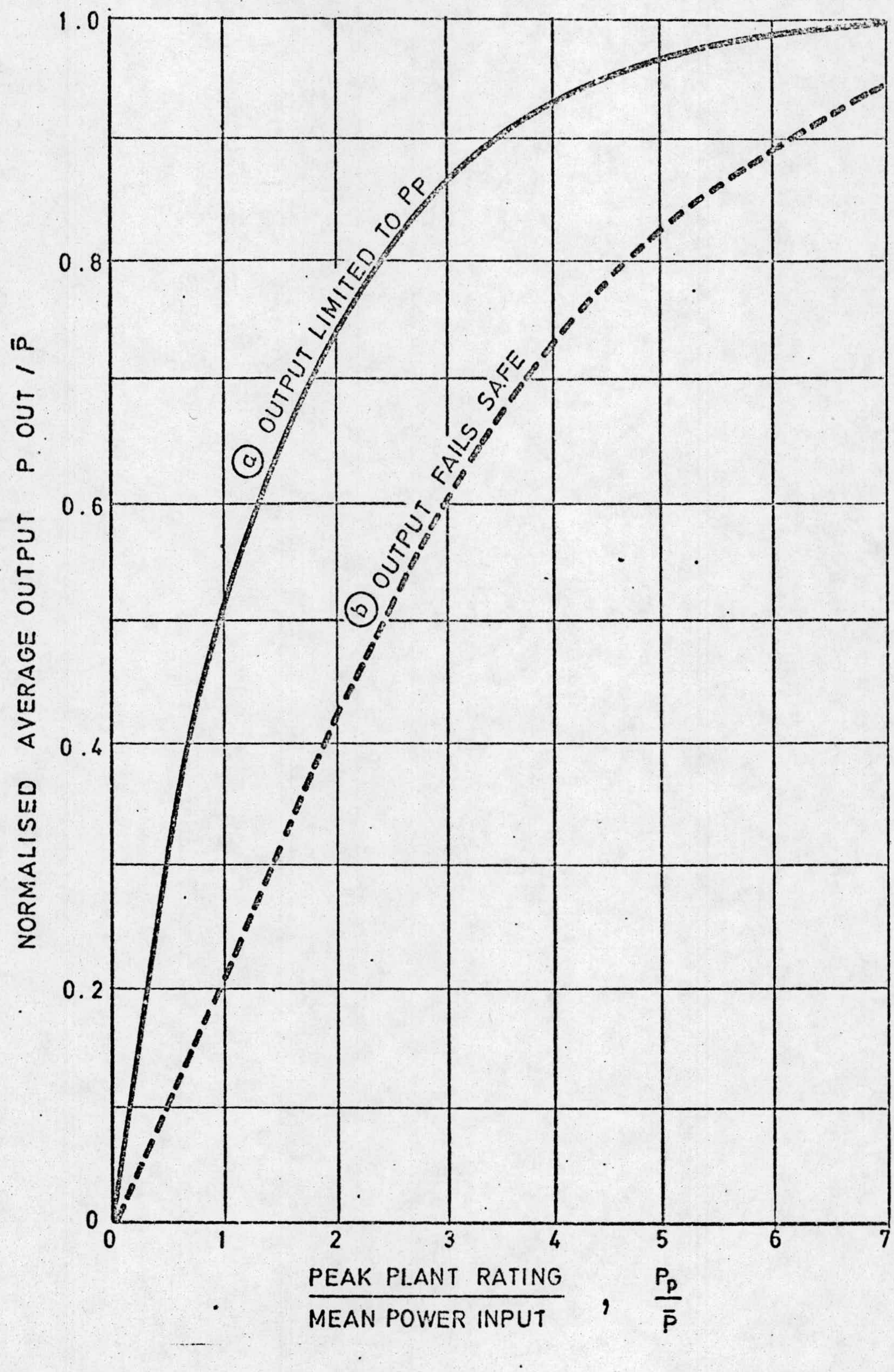
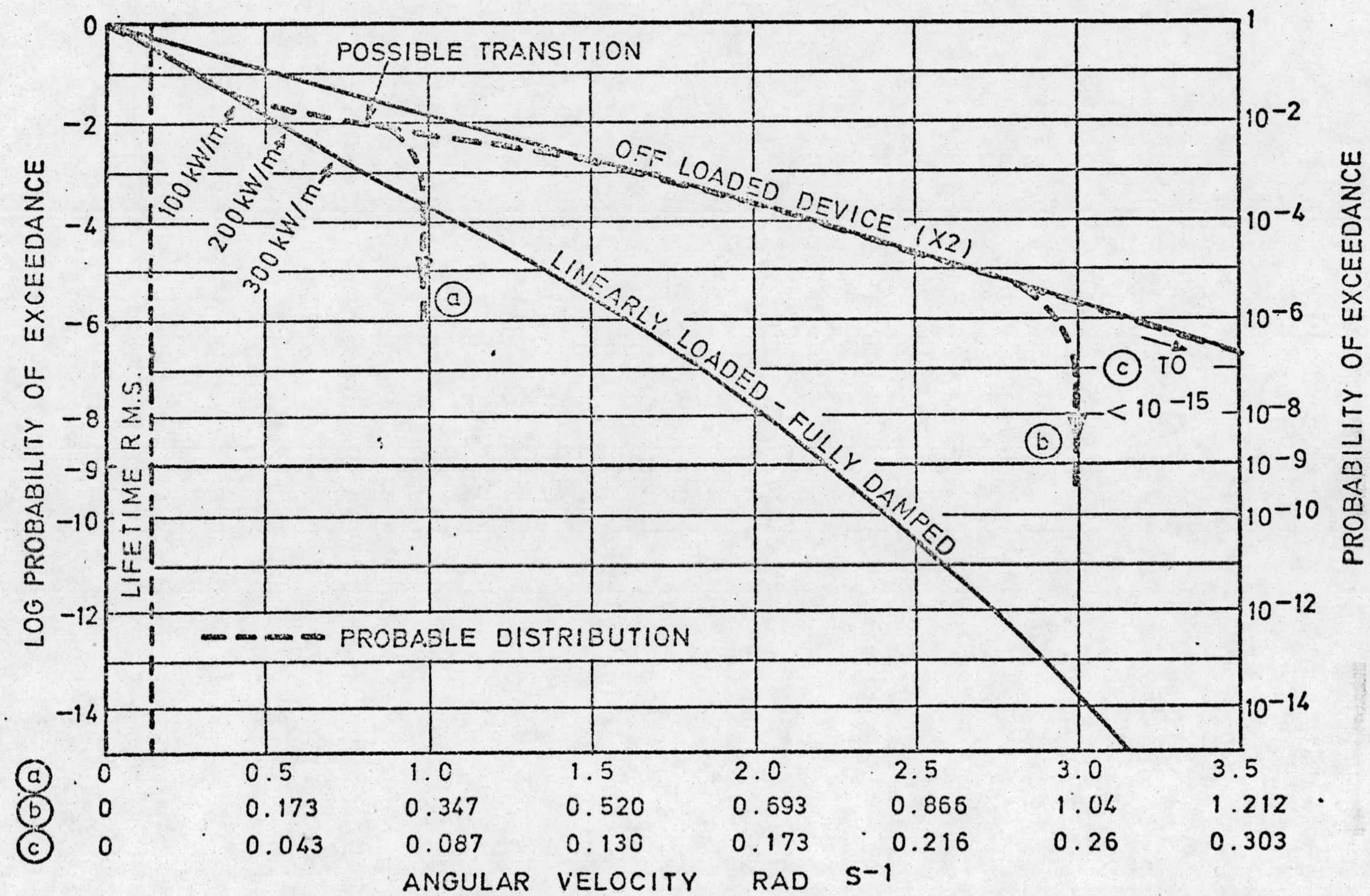
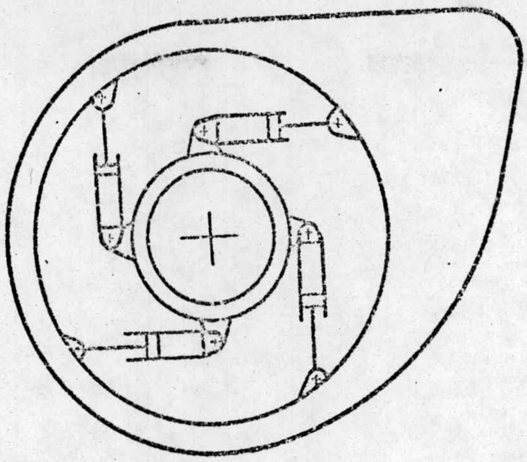


FIG. 6. GENERATING EFFICIENCY IN OVERLOAD CONDITIONS

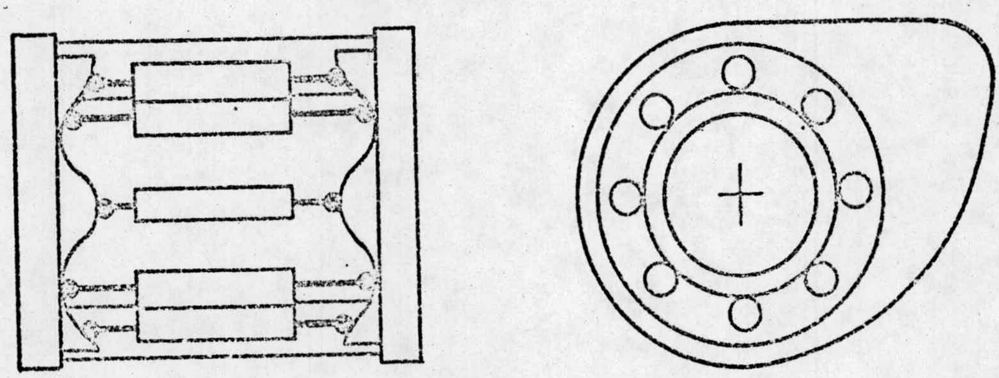


a 15m DUCK (THEORY - SMALL K)
b 20m DUCK (D0015)
c ' 30m RAFTS (CEGB)

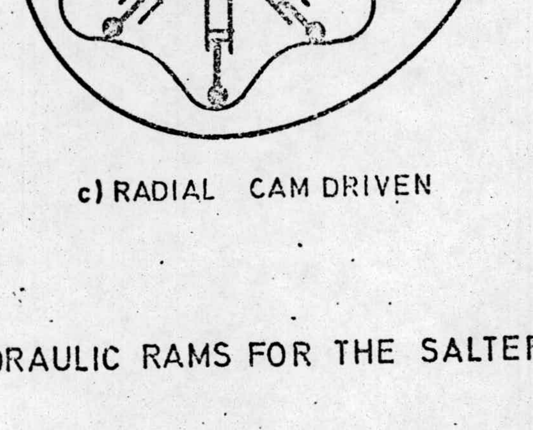
FIG. 7. ESTIMATED LIFETIME VELOCITY DISTRIBUTIONS



a) CRANKED

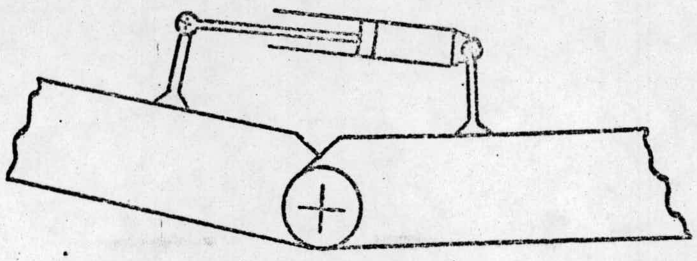


b) AXIAL CAM DRIVEN

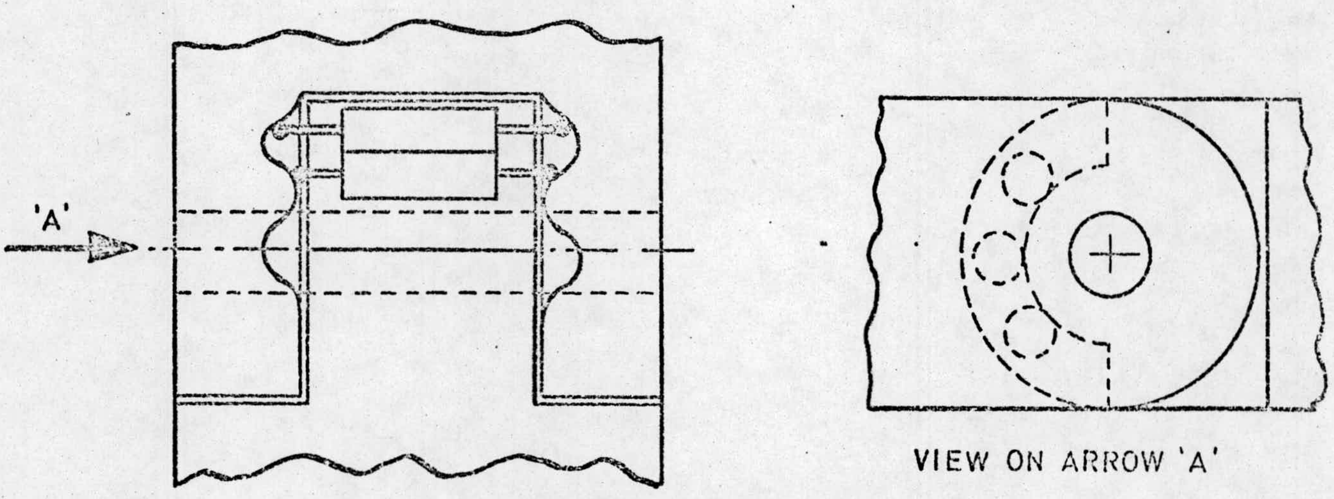


c) RADIAL CAM DRIVEN

FIG. 8 HYDRAULIC RAMS FOR THE SALTER DUCK

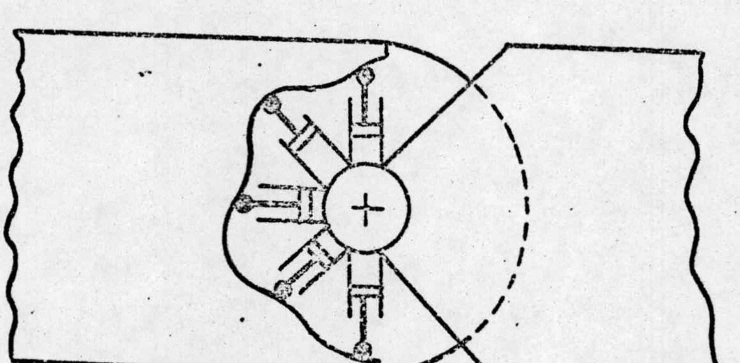


a. CRANKED



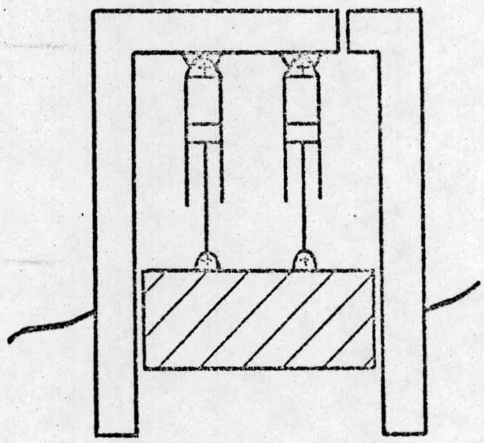
VIEW ON ARROW 'A'

b AXIAL CAM DRIVEN

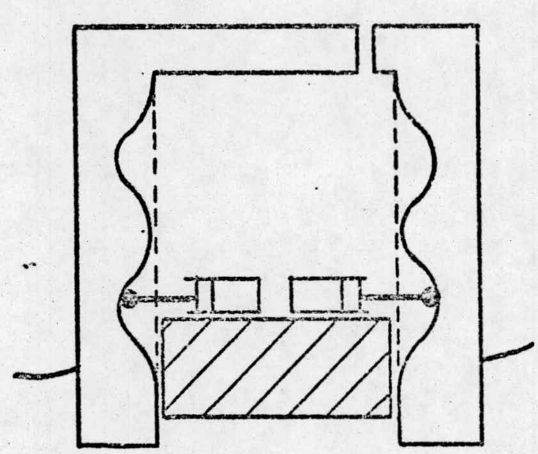


c RADIAL CAM DRIVEN

FIG. 9. HYDRAULIC RAMS FOR RAFT SYSTEMS

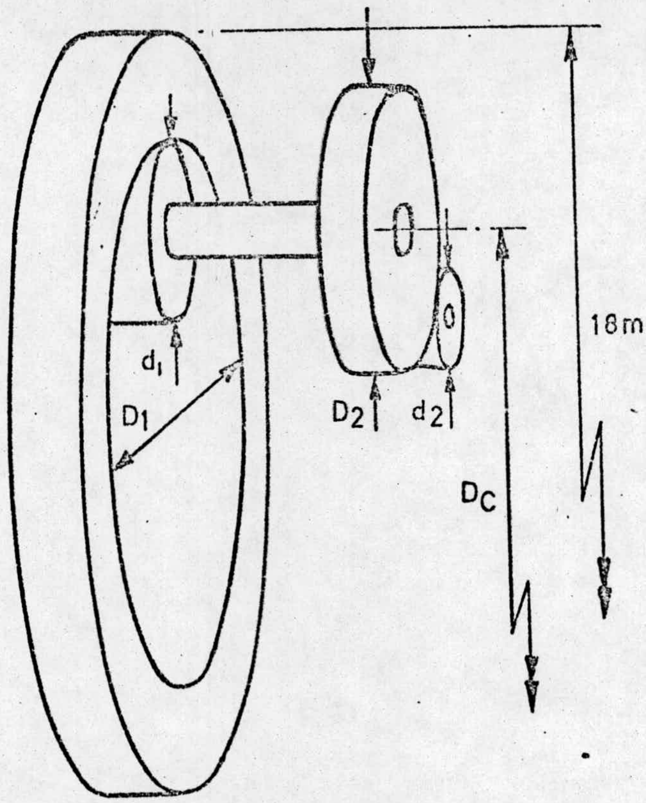


a) DIRECT DRIVE

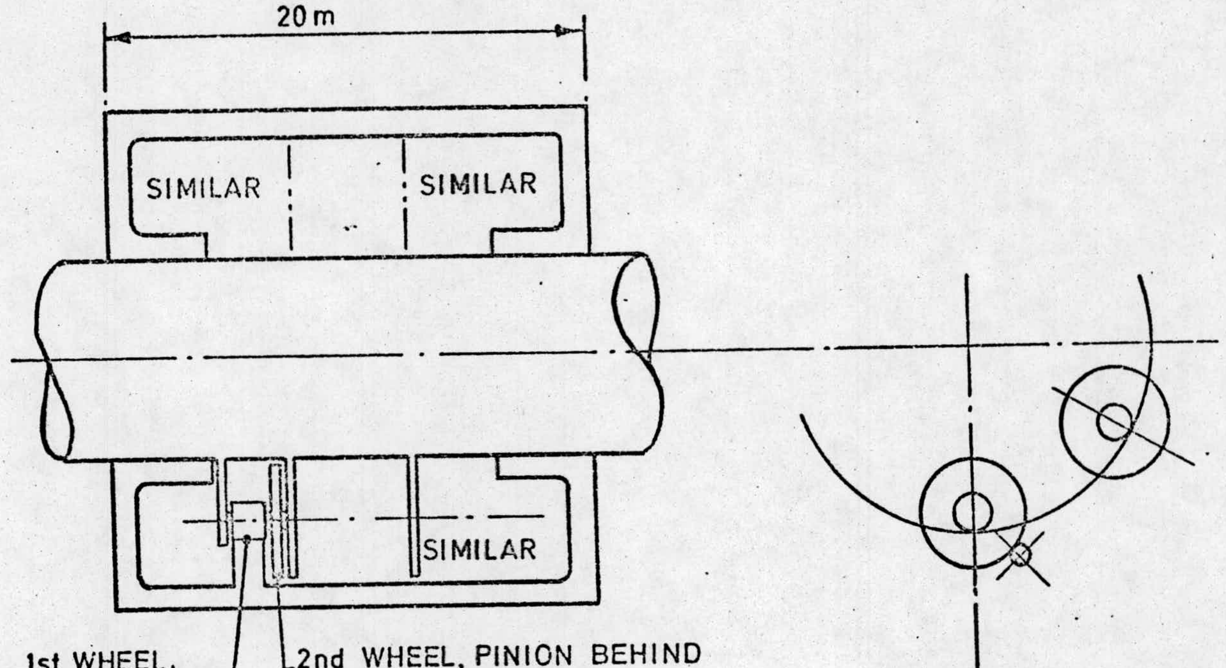


b) CAMFORM DRIVE

FIG. 10. HYDRAULIC RAMS FOR THE O.W.C.

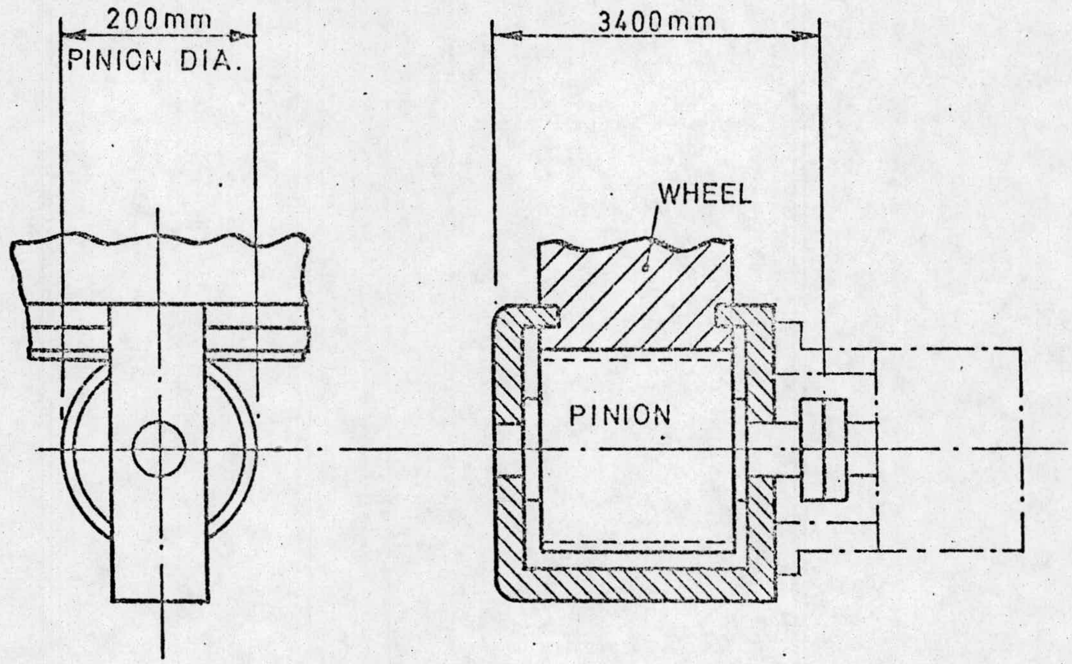


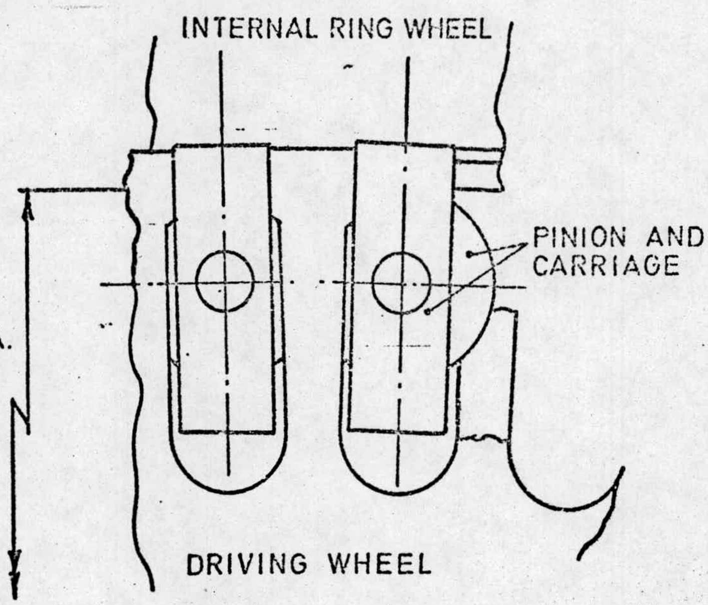
a. SCHEMATIC OF 2-STAGE GEARBOX



b. POSSIBLE LAYOUT IN A DUCK

FIG. 11. 2-STAGE GEARBOX FOR THE DUCK





GUIDED PINIONS WITHIN DRIVING WHEEL

FIG. 12. GUIDED PINIONS FOR THE DUCK

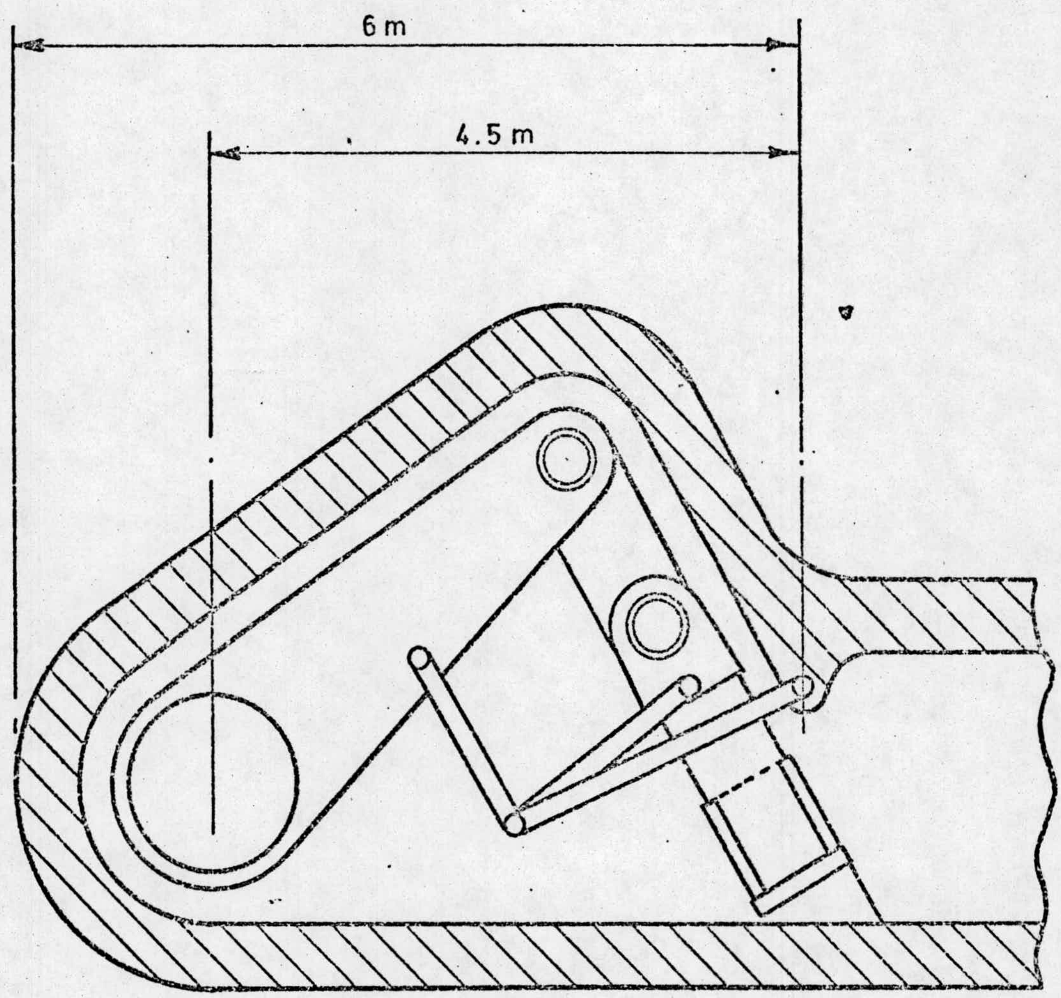
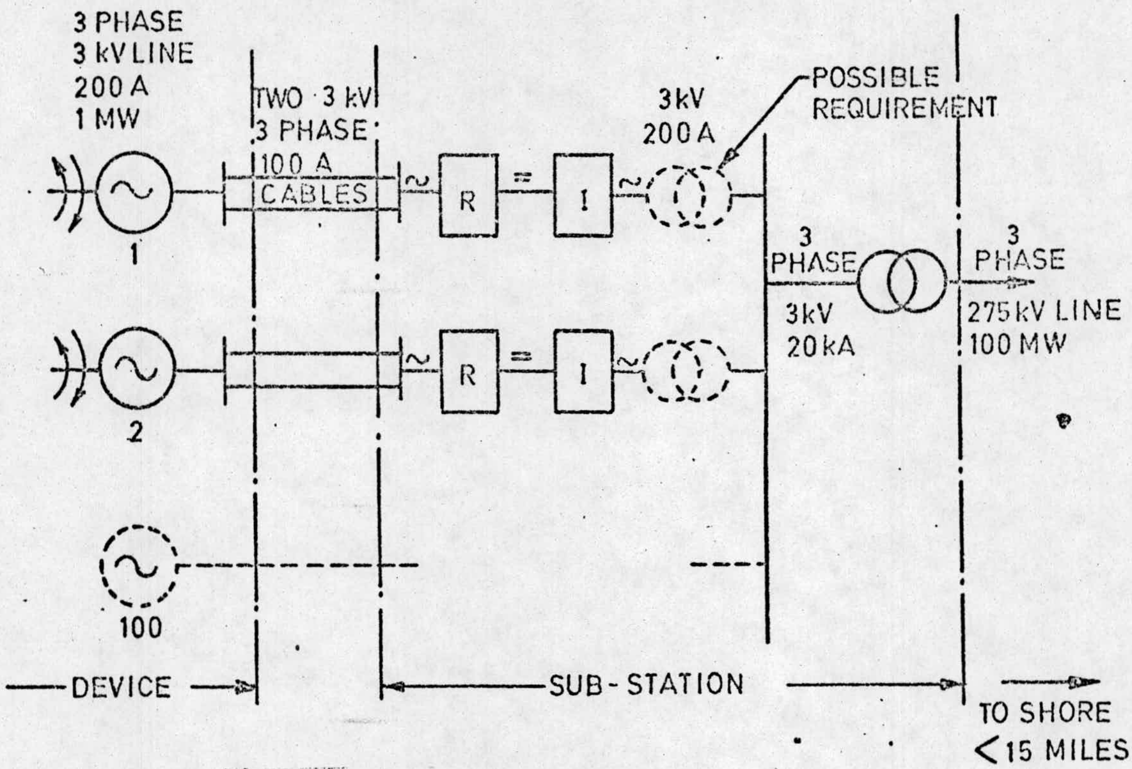
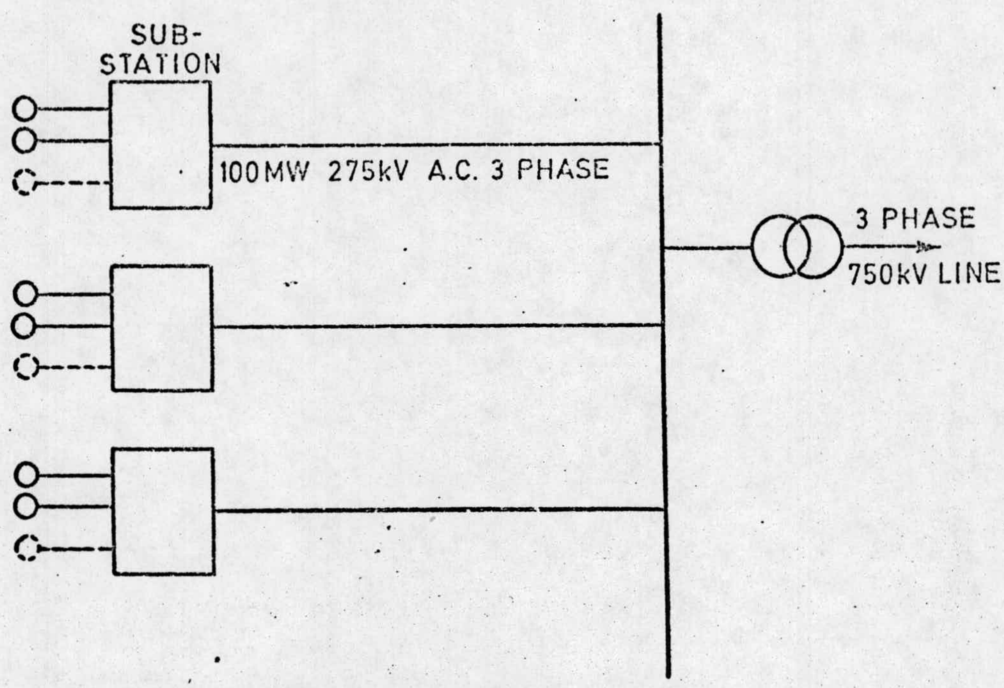


FIG. 13. A RAFT RAM DESIGN

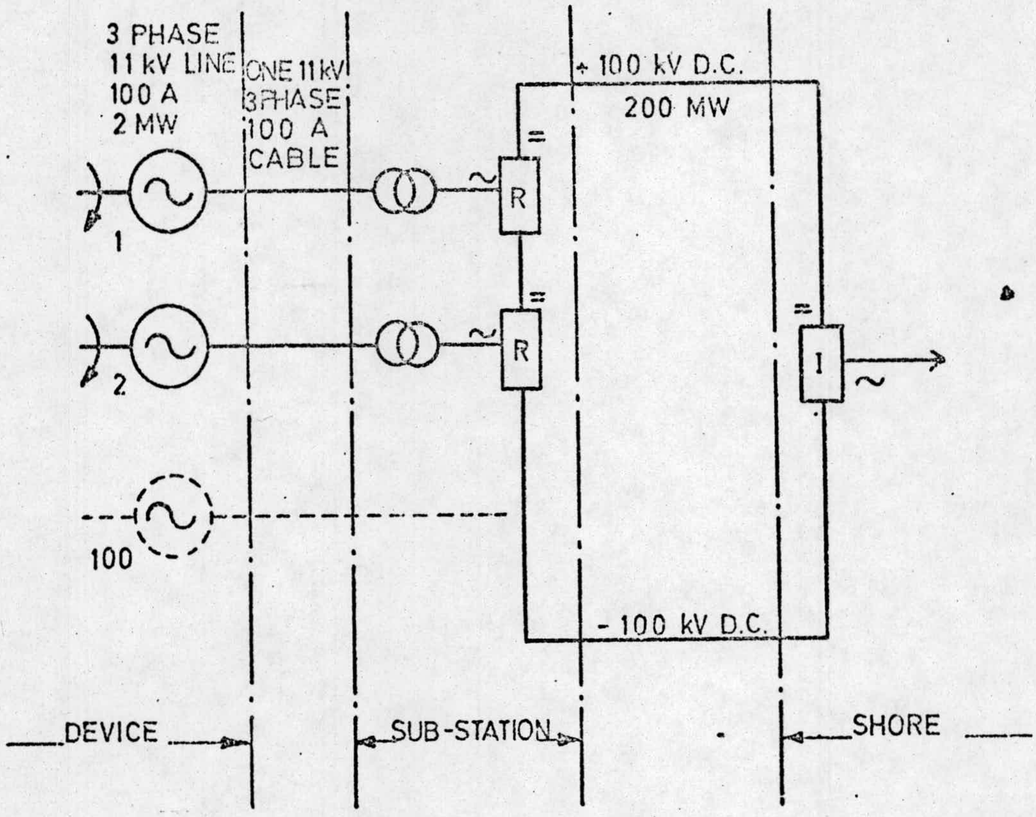


a. OFFSHORE EQUIPMENT

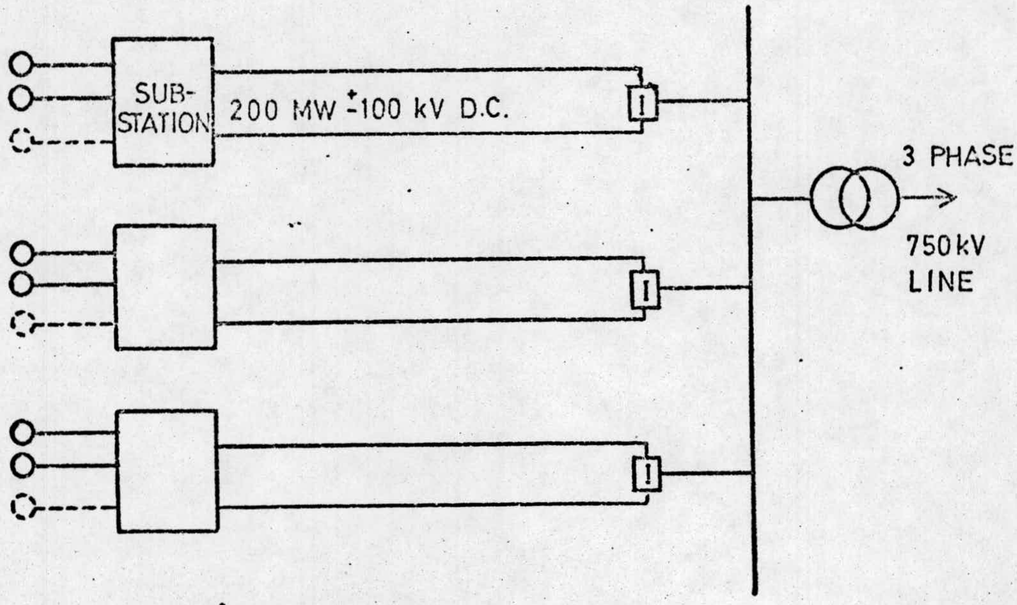


b. CONNECTION TO THE GRID

FIG. 14. DIRECTLY COUPLED SYSTEM WITH A.C. TRANSMISSION



a) BUILD UP OF A 200 MW MODULE



b) INTERCONNECTION TO THE GRID

FIG. 15 INDIRECTLY COUPLED SYSTEM WITH HVDC TRANSMISSION

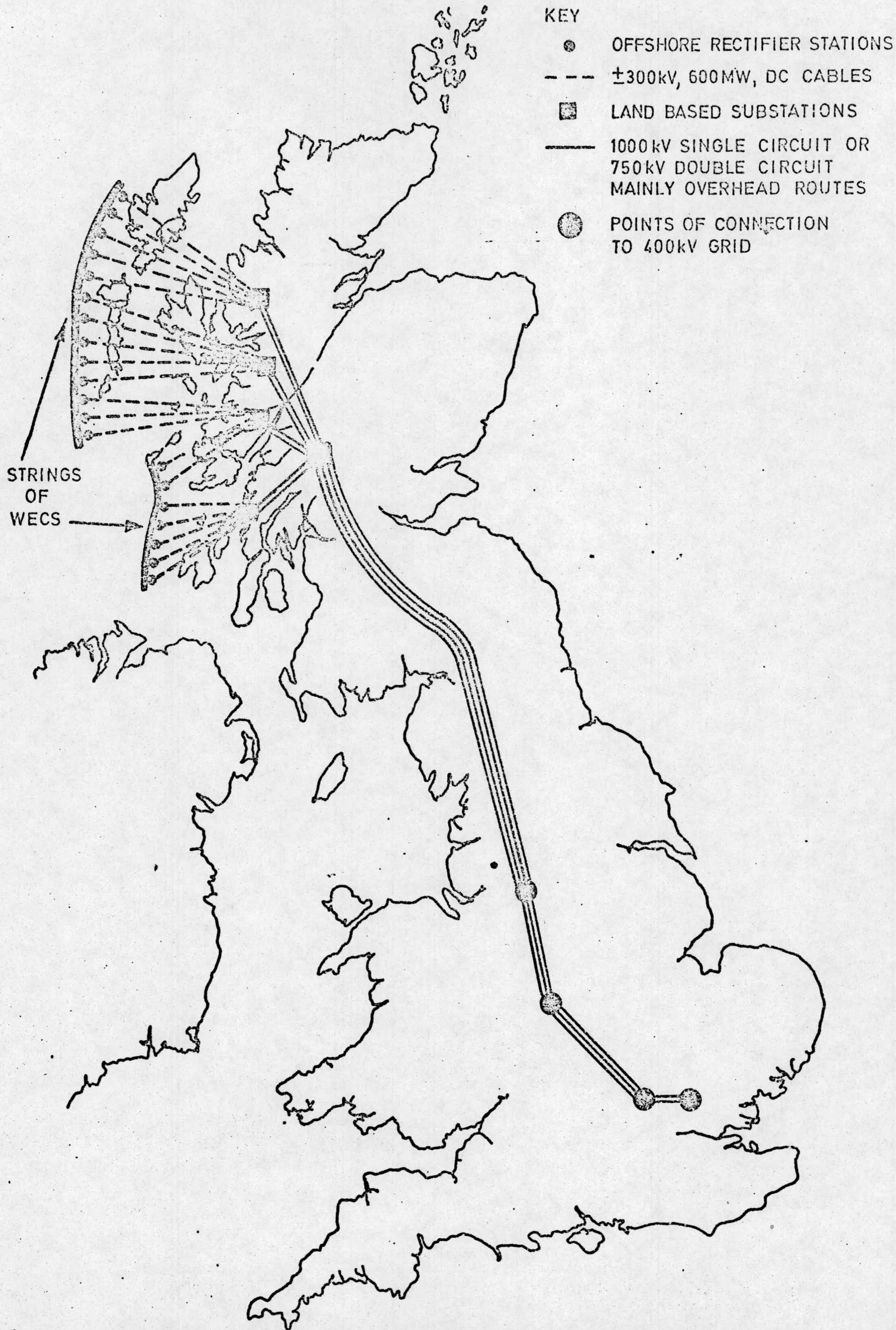


FIG. 16. POSSIBLE DEPLOYMENT OF 12GW OF WAVE ENERGY DEVICES AND CONSEQUENT ELECTRICAL TRANSMISSION REQUIREMENTS

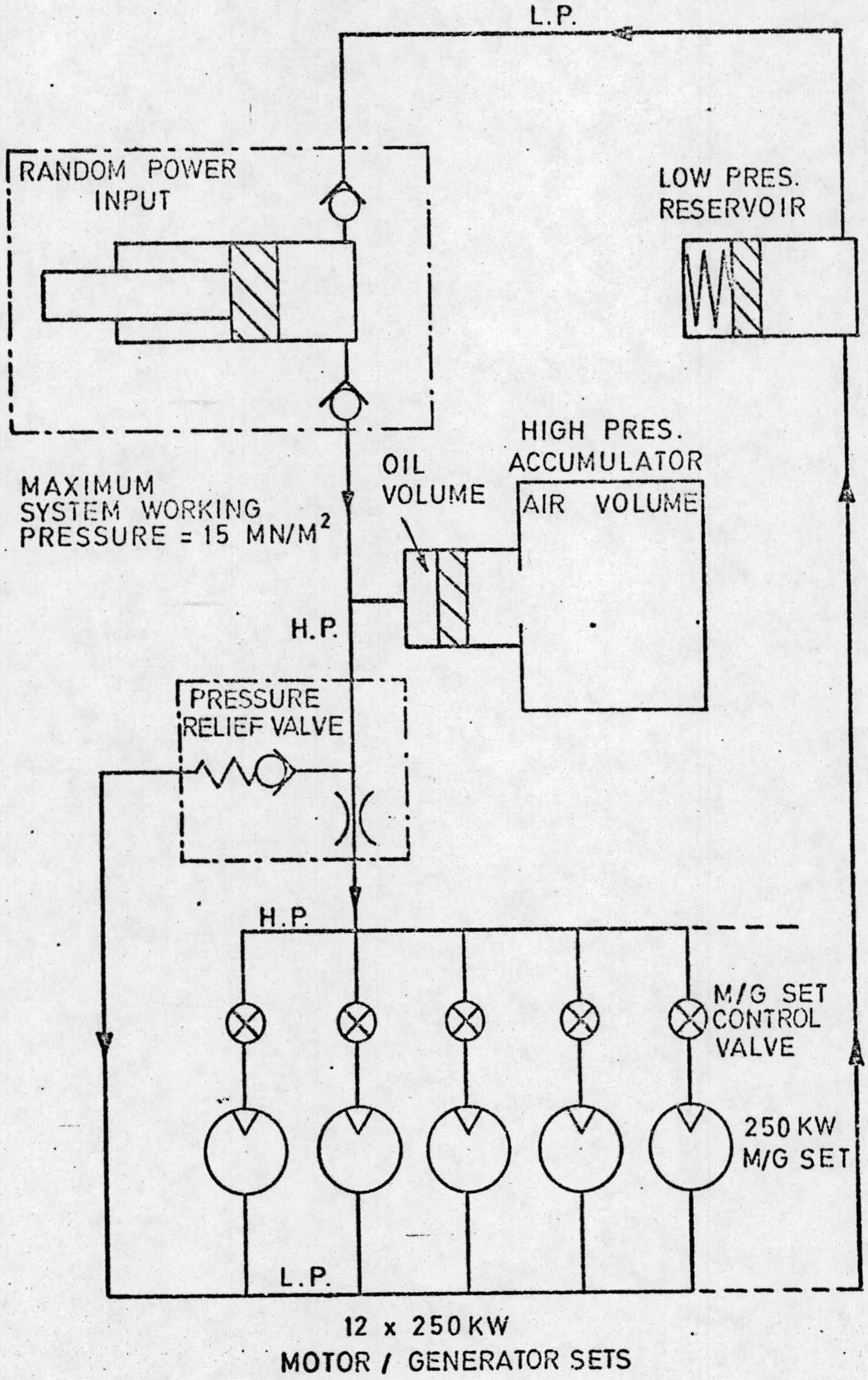


FIG. 17 HYDRAULIC / ELECTRIC SYSTEM MODEL

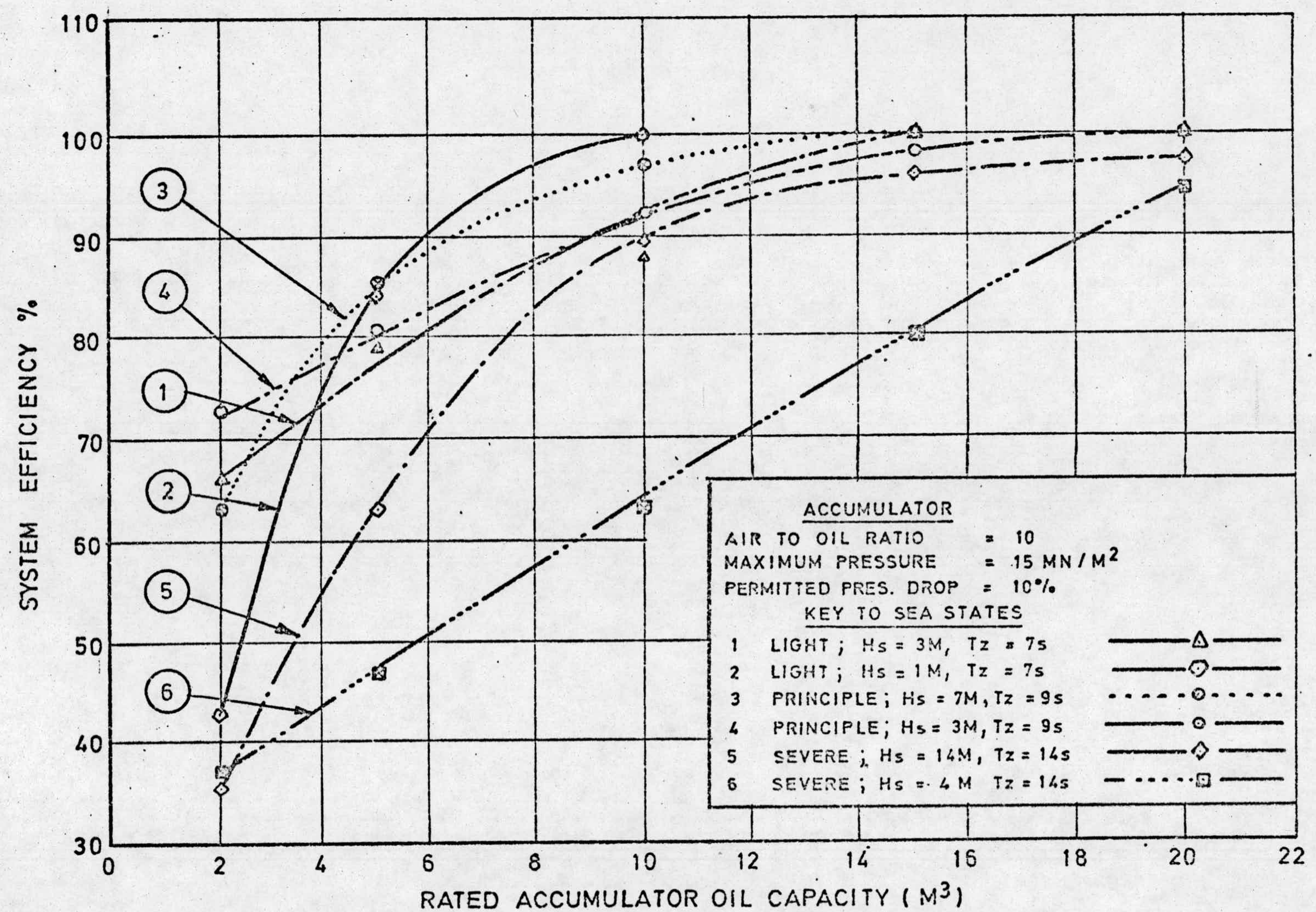
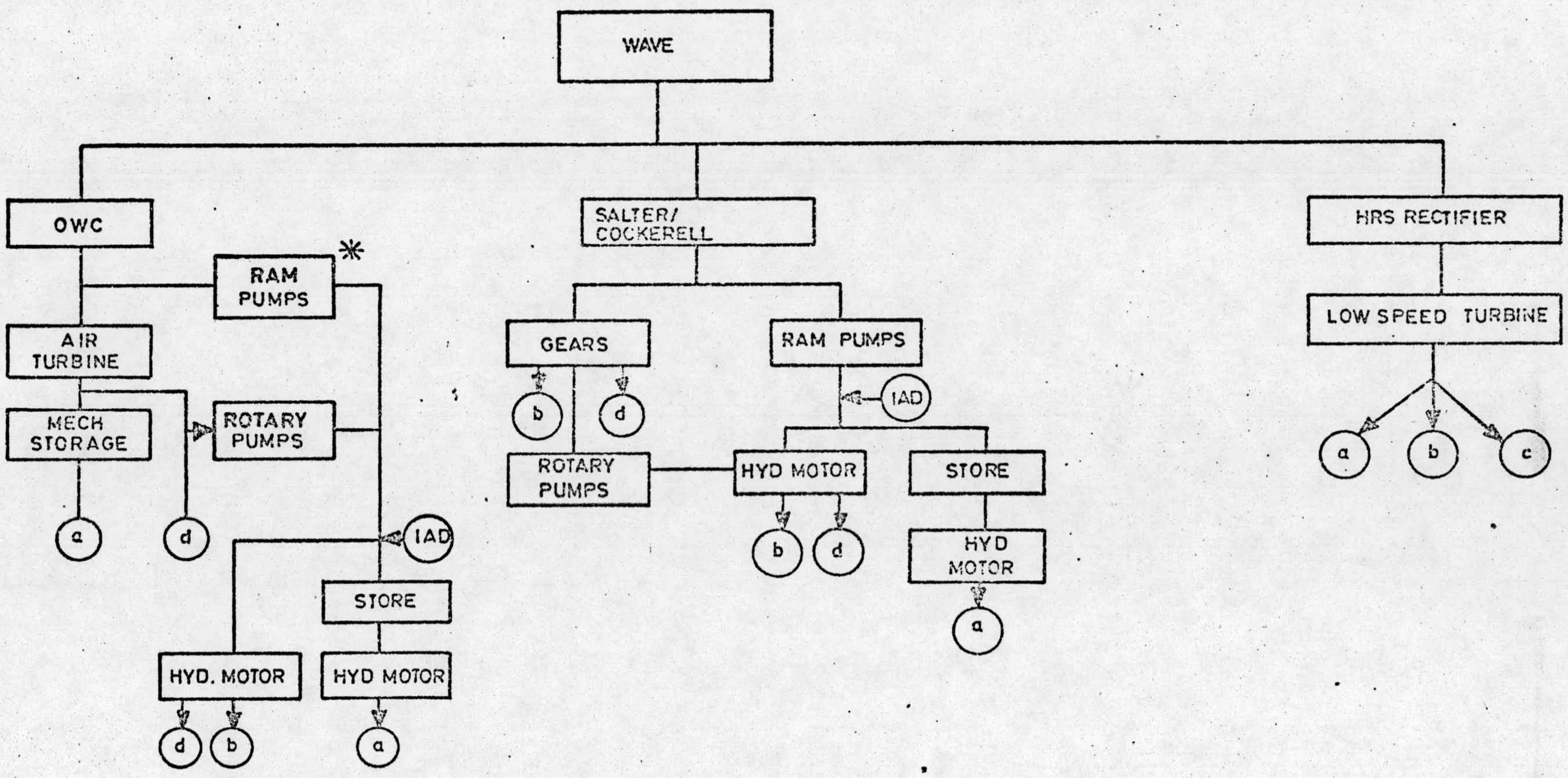
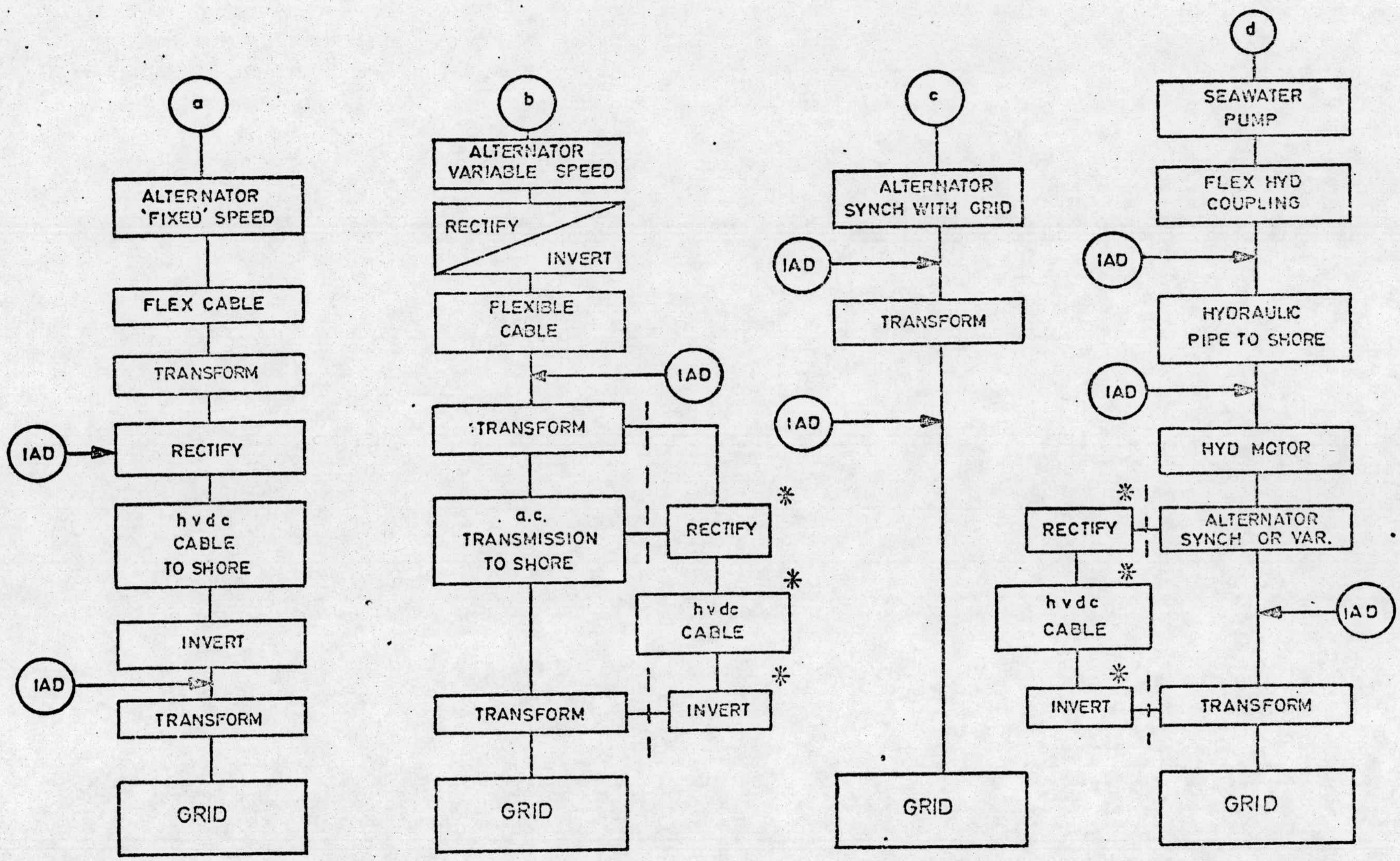


FIG. 18. RESULTS OF THE LUCAS MODEL STUDY ON THE EFFECT OF ACCUMULATOR SIZE ON HYDRAULIC/ELECTRIC SYSTEMS



* NON AIR TURBINE OPTION IAD = INPUT FROM ADJACENT DEVICE

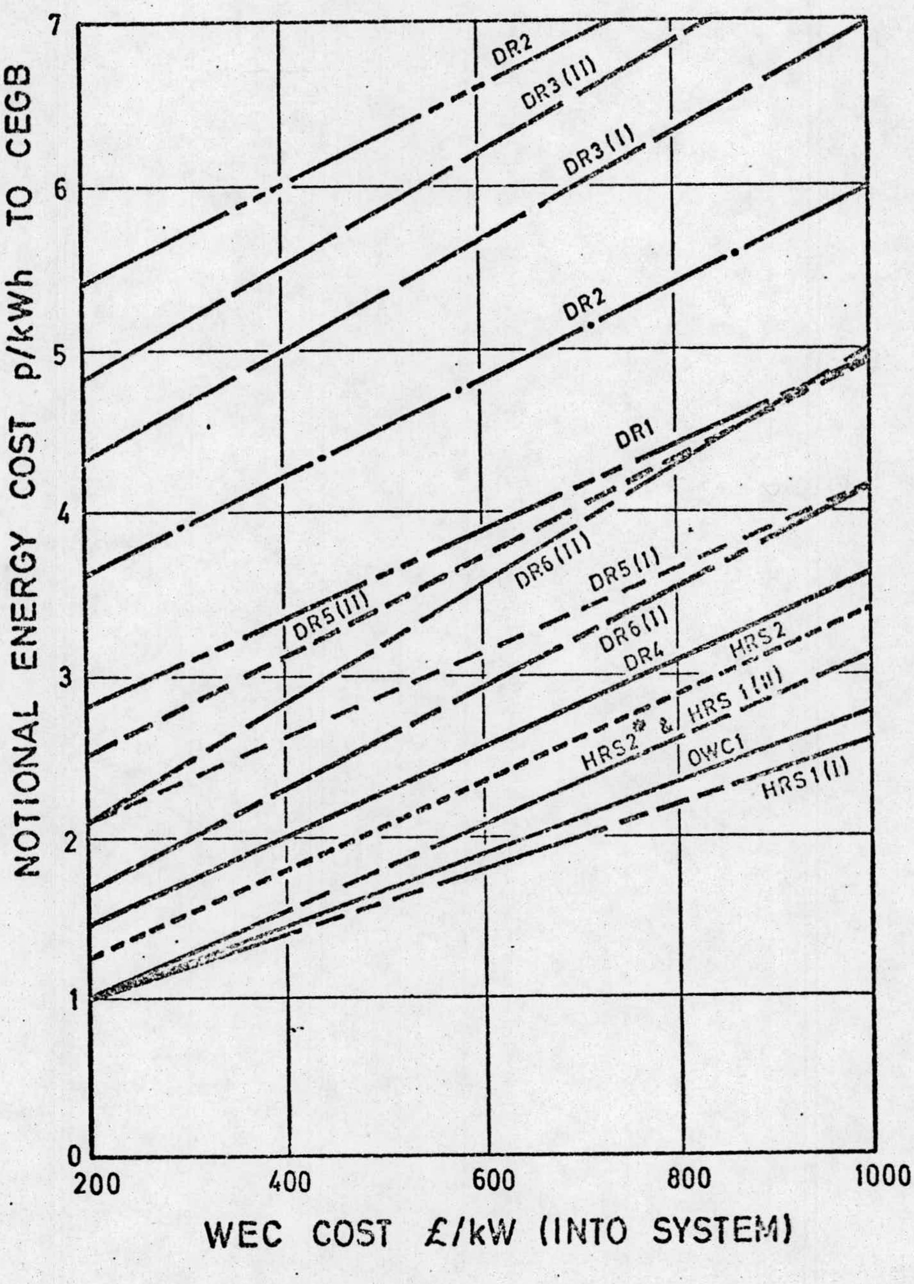
FIG 19 PRINCIPAL ROUTES LEADING TO AN ALTERNATOR DRIVE FOR ELECTRICAL TRANSMISSION (a), (b) and (c) AND TO HYDRAULIC TRANSMISSION (d). HYDROGEN ROUTE IS FROM (b) or (a).



NECESSARY ADDITIONS WHERE A LONG SUBMARINE ROUTE IS NECESSARY - E.G. FROM THE HEBRIDES

IAD = INPUT FROM ADJACENT DEVICE

FIG 20 PREFERRED TRANSMISSION ROUTES LEADING TO ELECTRICITY ON THE UK GRID



N.B. CARE SHOULD BE TAKEN IN INTERPRETING THIS FIGURE WHEN COMPARING DEVICES. THEIR CAPITAL COSTS MUST BE CALCULATED ON THE SAME BASIS.

FIG 21. NOTIONAL GENERATING COSTS BASED ON ESTIMATED SYSTEM COSTS AND A RANGE OF WEC COSTS EVALUATED AT A LOAD FACTOR OF 0·7.